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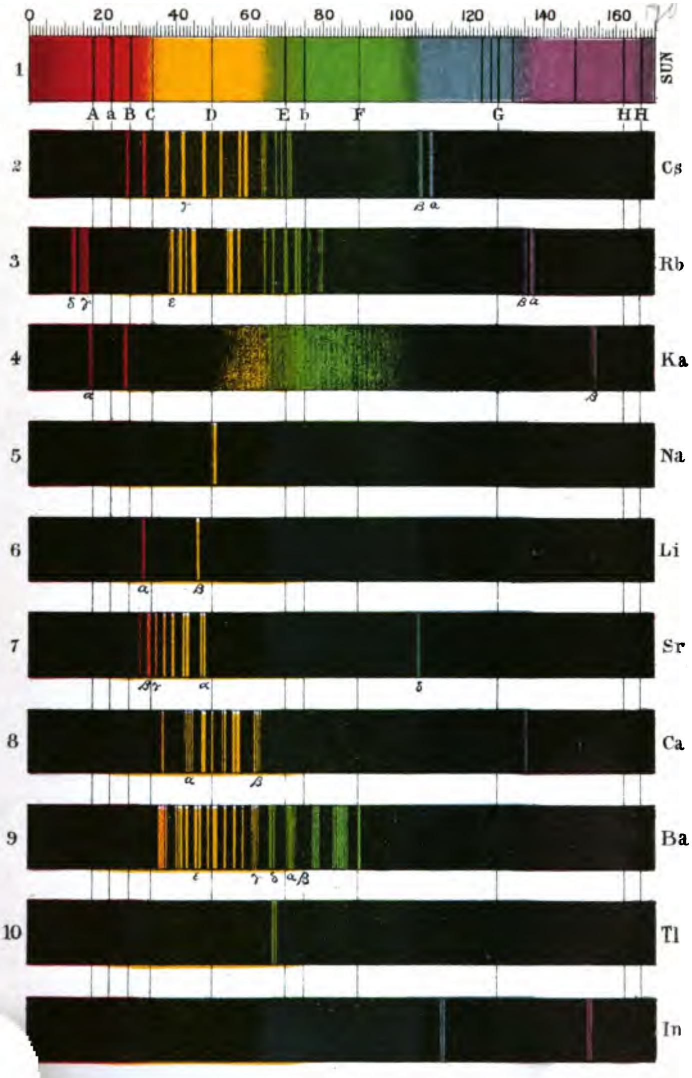

Collins' Advanced Science Series.

ACOUSTICS, LIGHT, AND HEAT.

BY

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PREFACE.

The present Treatise has been prepared in conformity with the Syllabus of the Government Department of Science and Art, as indicated for the Advanced Stage Examination.

As in my Elementary Work, so in this, I have endeavoured to give such succinct explanations, and these through the unsparing use of well-executed Diagrams, as, I trust, should render the acquisition of the more difficult and abstruse parts of the subjects of easy access to the Student.

Towards my assistance the notes of the late Dr. W. S. Davis, of Derby, who was to have undertaken the preparation of the work, were placed by the Publishers at my disposal. These, though chiefly of a fragmentary character, were of some advantage to me. Chap. I. in Acoustics, and the "Doctrine of Energy" in the Appendix, were written by Dr. Davis.

I have consulted, amongst other works, those of Tyndall, Maxwell, Ganot, Deschanel, and Lommel.

A number of solved problems are dispersed throughout the text, which, it is hoped, will prove of service to the Student; whilst in the Appendix are given the Examination Papers of the Department from 1872 to 1876 inclusive, which will be helpful in the way of indicating what is expected of him in the May Examinations.

William Lees.

St. Leonards, Morningside,
Edinburgh, *Nov.* 1876.

Erratum.—On page 146, 12th line from bottom, *for* "No. 2 frontispiece," *read* "No. 5 frontispiece."

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ACOUSTICS.

CHAPTER I.

INTRODUCTORY—WAVE MOTION.

1. Definitions.—The travel of a vibrating elastic body, from one extreme position to the opposite and *back again*, is called a *vibration*. Continental writers define a *vibration* to be the travel of the vibrating body from one extreme position to the opposite; this corresponds to our definition of an *oscillation* of a pendulum. There is, however, a great advantage in the English usage.

The distance travelled by a given point in a vibrating body, in passing from one extreme position to the opposite, is called the *amplitude of the vibration.*

The time occupied in a complete vibration is called the *time of vibration*, or *period.*

The number of vibrations performed in a given time is called the *rate of vibration.*

2. Propagation of a disturbance in an Elastic Body.—When an elastic body suffers disturbance at one part, the whole body does not become immediately affected; because it is not until the molecules first affected begin to approach or recede from the adjacent ones, that the latter begin to move, and these in their turn have to suffer a slight displacement before the next in order begin to move, and so on, to the more distant molecules in succession; time being lost at each communication of motion from one layer of molecules to the next.

Thus one part of a body may, for an appreciable time, suffer a considerable compression at one part, produced, say, by a blow, while the remaining portion is in its normal con-

dition. The compression, however, would quickly move forward and involve in its turn each molecule of the body. In this way a tension produced by a tug, a lateral vibration, and other peculiar movements, are propagated through elastic bodies, each layer of molcules being forced in succession to imitate the motion of the preceding one.

The state of disturbance which thus travels through an elastic body is called a *wave.*

There is another important point for consideration: the force which produced the original disturbance may immediately cease to act. The molecules upon which it acted directly, would then be the first to recover their original position; but, in doing so, would be carried into positions just the opposite to their former ones. The behaviour of these molecules would be repeated by the next layer, and so on, through the whole body. In this way, a wave of exactly opposite character would follow the first; an expansion would follow a compression; a compression would follow a tug; a lateral motion to the right would be followed by one to the left. These opposite waves would continue to succeed each other rapidly until the whole is brought into a state of rest.

3. Production of Waves by Vibrating Bodies.—It will be easily imagined, after what has just been said, that if a succession of impulses are communicated to an elastic body, a *series* of waves will be transmitted through it; also, if the impulses are of the same kind, and follow each other at regular intervals of time, that the waves will be alike and equidistant one from another.

4. Analysis of Wave Motion.—In the diagram (fig. 1), let the letters a, b, c, etc., represent a row of particles in a state of rest, and let the vertical lines through the letters represent the direction in which the particles will vibrate when disturbed.

Suppose a to be first disturbed, so as to set it vibrating in the vertical line drawn through it, and suppose a to influence b so as to cause it to vibrate in a similar manner to itself; but, as time is required for a to affect b, let the vibration of b be $\frac{1}{8}$ of the time of vibration behind a. In like manner, let each particle to the right commence vibrating in its turn, each being $\frac{1}{8}$ of a vibration behind the pre-

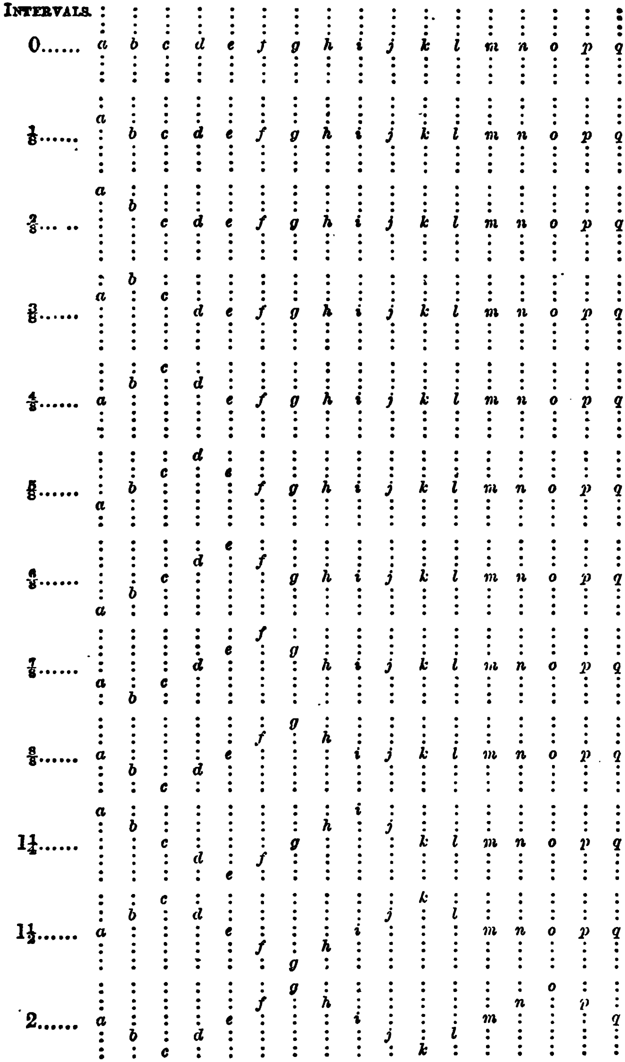


FIG. 1.—ANALYSIS OF WAVE MOTION.

ceding one. The consequence of these motions may be traced by observing the positions of the particles at the end of successive intervals of time—each $\frac{1}{8}$ of the period of vibration.

In $\frac{2}{8}$ of the period, *a* has reached the upper limit of its path, and is about to return; *b* is ascending, but is $\frac{1}{8}$ of a vibration behind *a*.

In $\frac{4}{8}$, *a* has descended to its initial position; *b* having reached its highest point in $\frac{3}{8}$ is now descending; *c* occupies its highest point.

In $\frac{6}{8}$, *a* has reached the lower limit of its path; *b, c, d*, are each descending; while *e* occupies its highest position.

In $\frac{8}{8}$, *a* has again reached its initial position. Having now performed a whole vibration, it is in the same relative position as it was when it began to move; *b* is ascending; *c* has reached its lowest position; *d, e, f*, are descending; while *g* occupies its highest position, and is followed by *h*.

The particles *a* to *l* are each performing different parts of their vibration, and are said to be in different *phases; a* is in the same phase as at the beginning; *e* is in its initial position like *a*, but as it is moving in the opposite direction, it is said to be in opposite phase to *a*.

In $1\frac{1}{2}$ of the period, *a* has performed three semi-vibrations; it is now in the same *position* as in $\frac{8}{8}$, but in opposite phase; in $\frac{8}{8}$ it was ascending, in $\frac{12}{8}$ it is descending.

In $\frac{16}{8}$, a double period, *a* has completed two vibrations.

5. Definitions.—Referring to the last row of particles in fig. 1, the series of particles *a* to *i*, inclusive, is called a *wave;* the position of these particles mark out a definite form, which is repeated by the particles *i* to *q*. The elevated portion, of which *g* is the highest point, is called the *crest;* and the depression, of which *c* is the lowest point, the *trough* of the wave.

The *length* of a wave is the distance from any one particle to the next in the same phase as itself; it is usually measured from the top of one crest to the top of the next, or from the bottom of one trough to the bottom of the next. Thus the length of the wave is the distance, either from *c* to *k*, or *g* to *o*.

The *propagation* of the wave is seen in fig. 1, by tracing the successive positions occupied by, say, the crest of the wave.

The propagation of the wave, it will be seen, is a propagation of a form; there is a transmission of energy, but not of matter.

The direction in which the line of particles lies is the direction of the propagation.

The plane in which the particles perform their vibrations is the *plane of the wave;* in the figure, their plane is that of the surface of the paper.

The particles in the kind of wave we are now considering, vibrate *across* the direction of propagation. The distance from one limit of the vibration to the opposite is called the *amplitude of the vibrating particle.*

The motion of each vibrating particle, like that of a pendulum, is not uniform in all parts of its path; its velocity increases in proceeding from the extremities, where it is *nil*, to it neutral position, where it is a maximum. If these variations of velocity were taken into account in the diagram, the forms of the crests and troughs would not be angular, but rounded.

The time taken by any one particle to complete a whole vibration is that required for any particular point in the wave form to move forward a whole wave-length, and is called the *period of the wave.* The number of waves passing a given point, in a given time, is *wave-frequency* or *rate.*

6. Simple Illustration of Wave Motion.—Take a long vulcanized india-rubber tube, attach one end firmly at a convenient height, then, taking hold of the free end, give it a sudden to and fro movement, so as to raise a protuberance upon the tube. The form of this protuberance will quickly move forward and reach the fixed end, where it will be reflected, and return to the hand. The protuberance, or crest, will be seen to be followed by a similar protuberance reversed, or trough; thus, a complete wave is formed by a movement of the hand to and fro.

A small wooden ball strung on the tube will be observed simply to move to and fro as the wave passes it, but will, of course, make no progressive motion.

If the tube be filled with sand, the motion of the wave will be much slower, and may be better followed by the eye.

7. Waves on the Surface of a Liquid.—The surface

waves of liquids may be studied by throwing a stone into a pool of still water, or, more conveniently, by tapping with the finger water contained in a large flat vessel. The water in the latter case should be blackened with a little ink and be illuminated by light from behind the experimenter. Waves on the surface of mercury are better seen, as they move more slowly and reflect more light.

Very regular waves may be set upon water or mercury, by means of a small metallic ball attached to the lower end of a spiral spring suspended vertically. The spring must be adjusted so that the ball, when at rest, just touches the liquid. The spring being set gently vibrating up and down, one wave is produced for each complete vibration; and as the vibrations of the spring are isochronous, and the velocity of each wave the same, it follows that the waves are all the same length.

8. Definition of "Wave-Front."—By observing the waves on water or mercury as they proceed from the centre of disturbance, it will be seen that they carve the surface into a series of circles, alternately elevated and depressed. Selecting any particle forming part of one of the waves, say a particle which, at a given moment, forms the highest point of a crest: it is evident that it will form part of a circle of particles, all in the same phase as itself. The circular line thus marked out is a *wave-front*. A wave-front may be defined as a line or surface formed by a series of particles in the same phase, and distant by the same number of wave-lengths from the centre of disturbance.

The wave-fronts on the surface of a liquid of uniform density are *circles;* those of sound waves in free homogeneous air are *spheres*.

9. Waves of Condensation and Rarefaction.—In the kind of waves described in Art. 4, the vibrating particles move *across* the direction of propagation. Waves of this kind cannot be formed in gases, from the want of cohesion between their molecules. Gases, however, and also liquids and elastic solids, are capable of propagating waves by a movement of their particles to and fro *in* the direction of propagation.

To understand this kind of wave motion, let *a, b, c,* etc., fig. 2, be a row of equidistant particles in a position of rest, and let

them be capable of vibrating in the direction of the row of letters themselves.

Suppose *a* to be first disturbed, so as to set it vibrating, and, for the sake of convenience, let the amplitude of its vibration be twice the space between any two particles. As in the example, fig. 1, let the time lost in the transfer of energy from *a* to *b* be such that *b* will be $\frac{1}{8}$ of a vibration behind *a*. In like manner, let each particle to the right commence vibrating in its turn, each being $\frac{1}{8}$ of a vibration behind the preceding one. The consequence of these motions will be evident on observing the positions of the particles at the end of successive eighths of the period of vibration. These are shown in fig. 2; it is unnecessary to give further explanation, as the remarks in Art. 4, with obvious modifications, apply also to this case.

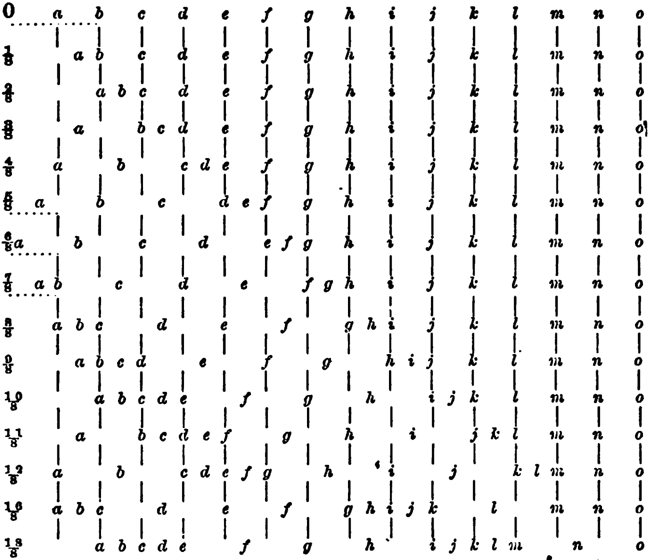


FIG. 2.—WAVES OF CONDENSATION AND RAREFACTION.

The series of particles, *a* to *i*, fig. 2 ($\frac{8}{8}$ to $\frac{18}{8}$), constitute a

wave, these two particles being in the same phase. The wave consists of two parts, a *condensation* and a *rarefaction*.

The distance from the centre of one condensation to the centre of the next, or from the centre of a rarefaction to the centre of the next, is the *length* of the wave.

The above is the character of the waves, produced in air by the vibrations of an elastic body, that is, *aërial* waves. These are also called *sound* waves, from their capability, within certain limits, of exciting the sensation of sound, when they reach the ear, through the air.

10. Illustrations.—To illustrate the propagation of an impulse in a manner somewhat resembling that just explained—take a number of solitaire balls and place them on a piece of board having a groove in it, so that they will lie in contact with each other in a straight line; now taking the terminal ball in the hand, roll it against the end of the row. In striking the second, the first comes to rest. No movement is observed in any of the balls except the last, which flies off with a velocity very nearly the same as that with which the first ball was struck. We have thus the energy of the first ball conveyed to the last without any direct motion of the intervening balls.

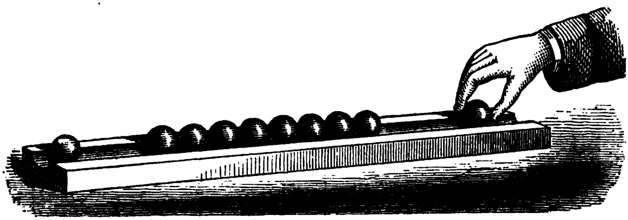


FIG. 3.—ILLUSTRATION WITH SOLITAIRE BALLS.

A much better method of illustrating waves of compression and rarefaction is by means of a long spiral spring of fine steel wire. This may be made by winding the wire with regularity of tension on a cylindrical rod about an inch in diameter. Each turn of the wire should be in close contact with the preceding one, and the winding continued until the spiral measures about 18 inches. The wire may then be liberated, and supported vertically between two fixed points, say a yard apart.

The apparatus being prepared, draw a small portion of the spring together and release it suddenly; the compression will be observed to pass up the spring, followed by an expanded portion, giving a complete representation of waves of compression and rarefaction. A piece of paper placed between two turns of the spring is seen to vibrate up and down as the wave passes it. These experiments may be made visible to a large audience by throwing a large shadow of the spiral upon a screen by means of the electric or lime light.

11. **Motion of the Air-particles not the same.**—In the explanatory diagram (fig. 2) it was convenient to suppose that the vibrating particles moved with uniform velocity in all parts of their paths; hence the wave was represented as consisting of a uniformly compressed half, and a uniformly rarefied half. But, as already stated, the vibrating particles, like the oscillating pendulum, have unequal velocities at different parts of their paths; their greatest velocity being acquired when passing their neutral point, from which position their velocity decreases towards either extremity of their paths, where it is zero. In consequence of this variation of velocity, the density of the wave becomes a maximum at the centre of the condensed part, from which position the density gradually diminishes to the centre of the rarefied part, where it is a minimum.

CHAPTER II.

VELOCITY OF SOUND—TRANSMISSION THROUGH GASES, LIQUIDS, AND SOLIDS.

12. Sound as a Physical Phenomenon.—All sensations arising from the healthy and normal action of the organs of sense, are merely mental translations of the influence of certain forms of energy on these organs, and which have an independent existence outside of us.

In the case of sound, that which is mentally translated as a particular sensation, pleasing or otherwise, arises in normal circumstances from the peculiar form of an aërial wave or waves, which enter the ear. The existence and form of these aërial waves, in their turn, depend on the vibrations of an elastic body, or bodies, and on the mode in which these vibrations are performed.

Sound, therefore, has a physical existence, independent of our organs of hearing; and the branch of science called *Acoustics* has for its object the investigation of all questions relating to the vibrations of elastic bodies, the waves they produce in surrounding media, and the action of these waves on other bodies. In these investigations the ear is the chief analytical agent, but it is only capable of dealing with vibrations within a certain range; hence much is embraced by acoustics which has no corresponding auditory sensation.

Vibrations, when slow enough, are observed by the eye, and even when too quick to be directly observed, we possess many means of rendering their existence visible.

Vibrations may also be felt. The deep notes of a powerful organ may often be felt as they impinge on the skin; even a deaf man feels them. Anyone lightly touching a vibrating bell feels its tremors.

13. Cause of Sound.—The *immediate* cause of sound is the vibration of the sounding body. This may be well illustrated

by taking a glass receiver (fig. 4), with a number of small wooden balls suspended from the top. If the receiver be struck with a mallet, the vibrations are rendered apparent by a peculiar dancing motion on the part of the little balls. These vibrations are communicated to the surrounding air, moulding it into a series of condensations and rarefactions which proceed in concentric spheres from the centre of disturbance, diminishing in effect, as they enlarge, with the distance. These sonorous waves enter our ears, excite the auditory nerve, and produce the sensation we call *sound.*

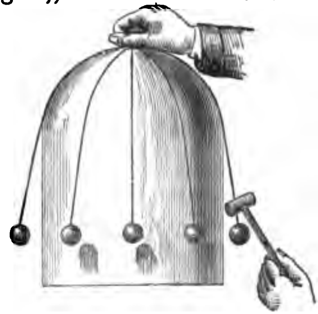


Fig. 4.—Receiver with Balls.

A careful study of Arts. 4 and 9 will render the precise mode of propagation apparent. Fig. 5 exhibits, by the difference in the shading, the varying disturbances given to the air-particles, as the waves proceed outwards. The distance from A to B, or from C to D, as before, constitutes the *length* of the sonorous wave.

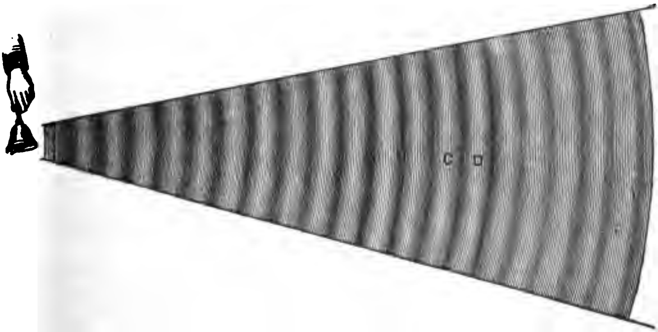


Fig. 5.—Propagation of Sonorous Waves.

14. Difference between Ordinary Motion and Wave Motion.—In ordinary motion, such as that of a cannon ball, the object moves bodily forwards.

In the case of a wave, such as that formed upon the surface of water, it is the form only which moves forward, the particles of the water only rising and falling as the crest or trough of the wave passes them. This may be seen by watching a small floating object, which rises and falls as the waves pass it, but is not itself moved onwards.

The same is the case with a wave of sound; the condensation and the rarefaction move onwards, but the particles of air have but a slight backward and forward movement.

15. Sound cannot pass through a Vacuum.—It is essential that there be some medium for the transmission of sound. The ordinary channel of conveyance is the air; but, as we shall afterwards see, there are other substances which convey sound. That sound cannot be transmitted through a vacuum is proved by the ordinary experiment of ringing a bell under the receiver of an air-pump. Fig. 6 shows a simple and inexpensive form of the apparatus. The bell is supported on a pad or cushion, so as to check, as far as possible, the passage of the sound to the plate of the air-pump. In proportion as the air is exhausted, the sound of the bell diminishes, and eventually becomes almost inaudible.

Fig. 6.—Bell Experiment.

This experiment proves also that the intensity of sound diminishes with the density of the air—a fact which is well known to those who ascend lofty mountains. Thus it is said that at the top of Mont Blanc the human voice is much weakened, and that the report of a pistol resembles the noise of a boy's pop-gun. It follows from such observations, that the loudest noises or explosions which take place on the earth's surface, could not be heard beyond the limits of the atmosphere.

16. Velocity of Sound in Air.—Many familiar observa-

tions show that sound occupies time in travelling; the flash of a sportsman's gun is seen by a distant spectator before he hears the sound; a workman's hammer is seen to fall before the blow is heard; a person near the end of a line of soldiers does not hear a single sound when they fire their muskets simultaneously, the more distant ones being heard after those which are nearer; in the discharge of a thunder cloud, the first peal of thunder is not heard until some time after the lightning flash is seen.

The velocity of sound in air has been determined experimentally by several celebrated observers, among whom are Arago, Moll and Van Beck, Parry and Regnault.

The method usually adopted by these observers was to fire a cannon at a suitable place, and to observe the interval elapsing between seeing the flash of light and hearing the sound at a measured distance from the gun; then dividing the distance by the observed time. This was the method adopted by Moll and Van Beck in 1823.

To obviate any error which might arise from the direction of the wind, guns were fired simultaneously from each station, the time elapsing between the perception of the flash and the sound was also observed at each station, and the mean of the two observations taken. Great accuracy was obtained by using chronometers with pendulums revolving in a conical form, so that the index could be stopped at any fraction of a second. The time occupied by the flash of light in travelling any terrestrial distance is practically inappreciable, and was therefore, in the experiment described, left out of account. After repeating the experiment many times, and making certain corrections, the result of Moll and Van Beck's research shows the velocity of sound in dry air, at 0° C., to be 1092·78 feet per second, or 333 metres per second.

Regnault obtained the velocity of sound in air by a method which obviated the necessity of relying on the perception of any individual. The experiments were made with large pipes prepared for the conveyance of water and gas in the neighbourhood of Paris. Tubes of length between 961 and 4886 metres were employed. The method of experiment was to close one end of the tube with a firm plate having a hole in the centre, through which a pistol could be fired, while

the distant end of the tube was closed by a sheet of caoutchouc. The firing of the pistol at one end of the tube was caused to break a galvanic current, which the movement of the caoutchouc sheet restored when the sound wave reached it. The exact moments at which the current was broken and made were registered on a revolving cylinder, together with the beats of a clock. By this means the time required for sound to travel the length of the tube was determined to a very small fraction of a second. Regnault's results give, for the velocity of sound at 0° C., 1085 feet per second. From these and such like observations, we may take the velocity of sound (0° C.) at about 1090 feet per second.

17. Influence of Elasticity and Density on the Velocity of Sound—Effect of Temperature.—The velocity of sound depends on the elasticity of the medium in relation to its density. It varies as the square root of the elasticity and inversely as the square root of the density. This relation is expressed by the formula—

$$V=\sqrt{\frac{E}{D}}$$

Where V = the velocity; E, the elasticity, as measured by the pressure applied, divided by the compression produced; and D the density. From this relation, it is clear that, if the elasticity and density of a medium vary in the same proportion, the velocity of sound remains constant. The law of Boyle* and Mariotte shows that this is the case with all gases within certain limits, provided that the temperature is constant. Applying this to the air, it means that the velocity of sound at all pressures—at the tops of mountains, or at the sea-level—does not vary if the temperature is constant.

We can understand, therefore, how temperature will affect the velocity of sound. An increase of temperature causes a decrease in the density of the air, whilst a decrease of tem-

* Boyle's or Marriotte's law is generally enunciated thus:—"The temperature being the same, the volume of a mass of air is inversely as the pressure it supports." Thus, if we have a mass of air occupying 1 cubic foot, at the ordinary pressure of the atmosphere (*i.e.*, 30 inches of mercury)—under a pressure of two atmospheres, it will occupy $\frac{1}{2}$ cubic foot, under 10 atmospheres $\frac{1}{10}$ cubic foot, and so on. It follows, of course, that the elasticity or pressure is in direct proportion to the density.

perature causes an increase in the density, the elasticity remaining the same. In the former case, therefore, sound travels *faster*, and in the latter case *slower*. From experiment, it appears that the velocity is increased about 2 feet for every 1° C., or 1·14 feet for every 1° F. At the temperature of 60° F., we may reckon, therefore, the velocity of sound to be about 1120 feet per second, or $12\frac{1}{2}$ miles per minute.

Hence, if the temperature of the air be given, we can find the velocity, and conversely.

EXAMPLE I.—What is the velocity of sound in air when the temperature is 11° C.?

Required velocity $=1090+22=1112$ per second. *Ans.*

EXAMPLE II.—What is the temperature of the air when the velocity of sound is 1102 feet per second?

Required temperature $=\frac{1102-1090}{2}=\frac{12}{2}=6°$ C. *Ans.*

18. Measurement of Distances by Light and Sound.—It is easy to see that distances may be measured by means of light and sound, the velocity of sound and the temperature of the air being known. The following examples are sufficiently illustrative:—

EXAMPLE I.—A cannon is fired, and an observer at a distance sees the flash, and five seconds afterwards hears the report; what is the distance of the cannon from the observer?

Sound travels over 1120 ft. per second (60° F.).
Therefore the distance required $=1120$ ft. $\times 5=5600$ ft.

EXAMPLE II.—You stand before a perpendicular cliff and shout, the echo of the sound reaches you five seconds afterwards; what is the distance between you and the cliff?

Distance travelled by sound in 5 seconds $=1120$ ft. $\times 5=5600$ ft.

But the sound goes and returns, so that the distance of the cliff is but half of this, viz., $\frac{5600}{2}=2800$ ft.

EXAMPLE III.—How many seconds will sound take to travel one mile?

1 mile $=5280$ ft. $\therefore$ Time required $=\frac{5280}{1120}=4\frac{5}{7}$ seconds.

19. Changes of Temperature in a Wave of Sound.—The temperature of air is raised by compression, and lowered by expansion. Experimental demonstrations of this will be found in another place. Applying this law to a sound wave passing through air, we observe that the condensed part of the wave must have a higher, and the rarefied portion a lower

temperature than the actual temperature of the air when at rest. The *average* temperature of the air, however, remains the same.

The effect of the increase of temperature on the condensed part of the wave is to confer on it greater elasticity; theretore, when at its maximum compression, it more quickly expands to regain its normal pressure, thus augmenting the velocity of the condensed wave. The effect of decrease of temperature on the rarefied part of the wave is to decrease its elasticity, so that it offers less resistance to compression; therefore it more quickly becomes condensed, thus augmenting the velocity of the rarefied wave.

Hence, both effects conspire to increase the velocity of sound. The increase in the velocity of sound in air, due to this cause, is about one-sixth more than what the velocity would be were there no such changes of temperature.

20. Newton's Calculation of the Velocity of Sound—Laplace's Correction.—Sir Isaac Newton calculated, mathematically, the velocity of sound at 0° C. to be 916 feet. He took into account only the change of elasticity, resulting from a change of density, but entirely overlooked the augmentation of elasticity due to the heat developed by compression. He accounted for the discrepancy between the velocity as determined from theory and from observation, by supposing that sound occupied time in passing from particle to particle of the air, but that its transmission *in* the particles themselves was instantaneous.

Laplace was the first to show the true cause of this discrepancy, and applied a correction to Newton's investigation, which brings the theoretical velocity into complete accordance with the observed velocity. Laplace's correction consists in multiplying the velocity as calculated by Newton, by the square root of the ratio of the specific heat of air at constant pressure (C^p) to its specific heat at constant volume (C^v), see Art. 237. Thus, if V be the calculated velocity, and V′ the true velocity, then—

$$V' = V\sqrt{\frac{C^p}{C^v}}$$

The value of the ratio $\frac{C^p}{C^v}$ is 1.414, hence we have the true velocity $= 916 \times \sqrt{1{\cdot}414} = 1090.04$.

21. Transmission of Sound in Liquids.—The velocity of sound in water has been obtained by direct experiments. Colladon and Sturm made the determination in the water of the Lake of Geneva in 1827. A large bell was suspended in the water and struck with a hammer, the sound of which was listened to at a distance, by means of a tube having a wide spoon-shaped orifice at its lower end, turned towards the origin of the sound. In the first experiments, a bell weighing 500 kilogrammes ($\frac{1}{2}$ ton) was used, sunk 3 metres in the water. The sound of the blow was heard through the water at a distance of 35,000 metres (nearly 22 miles). Afterwards, with a smaller bell, sunk 1 metre in the water the sound was heard at the distance of 13,487 metres (more than 8 miles). In these latter experiments, the hammer was worked by a lever in such a manner as to ignite a small quantity of gunpowder at the same moment that the hammer struck the bell. The time intervening between the perception of the flash and the sound was observed at a known distance, from which data the velocity of sound in the water, (its temperature being 8·1° C.), was computed to be 1435 metres, or 4708 feet, per second.

It will be observed that the velocity of sound in water is more than four times as great as its velocity in air, although water is 770 times as dense as air. The reason is, that although the density of water is so much greater than that of air, yet its elasticity, as measured by its resistance to compression, is greater still. The propagation of sound through liquids is believed to take place in the same manner as through air; but it has been found that the changes of temperature produced in the sonorous wave have little or no influence on the velocity, herein differing from what holds good with reference to air.

The formula $V = \sqrt{\frac{E}{D}}$ is equally applicable to liquids and solids—to the latter, however, only under certain restrictions.

22. Transmission of Sound in Solids.—That solids are capable of conveying sound is proved in many ways. The slightest tap with the finger at one end of a poker, can be distinctly heard at the other. By placing one end of a stick

on the lid of a boiling kettle, and listening at the other, the noise produced by the ebullition of the water is rendered very audible. The approach of a body of cavalry at a distance can be readily detected by applying the ear to the ground. The peculiar noise heard when near a telegraph post is familiar to every one—the tremors of the wires caused by the action of the wind upon them are conveyed through the post with great readiness. Airy remarks that "there are instances of people totally deaf to sounds produced by excitement in the air, but who can hear the sound of a watch, or a bell, when held by the teeth; the sound being conveyed by the bony and other portions of the head to the auditory nerves."

We here give a table of the velocities through different substances. Most of the results are those of Wertheim.

VELOCITY OF SOUND THROUGH DIFFERENT SUBSTANCES.

	Temp.	Feet per Sec.
GASES.		
Oxygen,	0°C.	1030
Hydrogen,	,,	4164
Carbonic Acid,	,,	858
Carbonic Oxide,	,,	1107
LIQUIDS.		
Solution of Common Salt,	18°C.	5132
Solution of Carbonate of Soda,	22°	5230
Solution of Chloride of Calcium,	23°	6493
Common Alcohol,	20°	4218
Sulphuric Ether,	0°	3801
SOLIDS.		
Lead,	20°C.	4030
Gold,	,,	5717
Silver,	,,	8553
Copper,	,,	11,666
Iron,	,,	16,822
Fir (along fibre),		15,218
Beech, ,,		10,965
Oak, ,,		12,622
Ash, ,,		15,314

From this table it appears that the velocity of sound through liquids is greater than through gases, and still greater through certain solids. The reason is, that the *elasticity of a liquid, in proportion to its density*, is greater than in a gas, and this relation is greater still in most solids.

The influence of temperature on the elasticity of solids is generally the reverse of what it is in the case of liquids and gases, the general effect of a rise of temperature being to *decrease* the elasticity of the solid, and hence the velocity of sound in it. The elasticity of iron and silver, however, increases with the temperature up to a certain point, but afterwards follows the general law.

23. Influence of Molecular Structure on the Velocity of Sound.—The elasticity of liquids and gases is the same in all directions, but the molecular structure of many solids—wood for example—renders them differently elastic in different directions. Hence the velocity of sound in these solids is not the same in all directions.

The elasticity of wood is greatest along the fibre; the velocity of sound in wood is, therefore, greatest in this direction. It is least *across* the fibre. The velocity of sound in wood is two to four times greater along the fibre than *across* the grain in any direction.

24. Intensity of Sound.—The bell experiment (Art. 15) showed us that the *intensity* of sound depended upon the density of the air. We have now to notice several other conditions which affect it.

(1.) The intensity depends upon the distance from the sounding body. When a sound is emitted in air, it is propagated in spherical waves, which as they advance get larger and larger. As the amount of force remains the same, but is distributed through a gradually increasing bulk of air, the intensity must get less and less. It is easily proved that, in free homogeneous air the intensity varies as the square of the distance. Thus—

The distances being as, . . .	$1, 2, 3, 4, \frac{1}{2}, \frac{1}{3}$,
The intensities are as, . . .	$1, \frac{1}{4}, \frac{1}{9}, \frac{1}{16}, 4, 9$.

This is known as the *law of inverse squares*.

(2.) The intensity depends upon the density of the air in which the sound is generated, not upon that in which it is heard. Thus, if two observers be stationed at A and B, one on the top of a mountain and the other on the plain below, at equal distances from a gun at G (fig. 7), the report of the gun will have the same loudness to each, though the air at A is more rarefied than at B. If, however, there be two

guns, giving at the *same* place reports of equal loudness; then when placed at A and B respectively—to an observer stationed at G, the gun at B will give a louder report than the gun at A.

Fig. 7.—INTENSITY OF SOUND.

(3.) The intensity depends upon the amplitude of the vibration. The relation between the two is expressed more strictly by the following law: *the intensity is in proportion to the square of the amplitude.* Thus—

The amplitudes being as 1, 2, 3, 4, $\frac{1}{2}$, $\frac{1}{3}$,
The intensities are as 1, 4, 9, 16, $\frac{1}{4}$, $\frac{1}{9}$.

The distances to which sound will reach depend upon the intensity, as well as upon the medium, in which it is generated. Thus the ticking of the same watch may be heard in water at a distance of 23 feet, in alcohol at a distance of 13 feet, and in air at a distance of only 10 feet. It is said that the firing of the guns at the citadel of Antwerp in 1832, was heard in the mines of Saxony, a distance of 370 miles.

The greatest distance to which sound has been known to be conveyed through the atmosphere, was on the occasion of a violent outburst of a volcano in the island of St. Vincent. It is recorded that the noise was heard at Demerara, a distance of nearly 350 miles.

Tyndall made lately some interesting experiments on what he appropriately calls "*the acoustic* transparency and opacity of the atmosphere." The general result he arrived at was, that a non-homogeneous atmosphere was unfavourable to the transmission of sound—a clear, sultry, still day, for instance, is not so favourable as a thick foggy day. This is accounted for by the scattering of the sound-waves by repeated reflexions from stratum to stratum of air of varying density. It may be due also to the effects of refraction. (See Art. 29).

CHAPTER III.

REFLEXION OF SOUND—THE EAR—INTERFERENCE.

25. Reflexion of Sound.—Sound is always reflected when it falls upon hard, unyielding obstacles. The apparent strengthening of the voice which is observed in large empty rooms is an effect depending on the reflexion of the sonorous waves by the walls and other hard surfaces; the reflected waves reach the ears from all parts of the room, and are heard almost at the same time as the direct sound, thus giving the observed fullness to the voice. This effect is not heard to the same extent in furnished rooms, or rooms full of people, in consequence of the sonorous waves being absorbed by the inelastic drapery and bodies of persons present.

The law in regard to the reflexion of sound is the same as that which holds good of light (see Art. 83).

26. Echoes.—These are due to the regular reflexion of waves of sound. In order that an echo be distinctly heard, it is necessary that the reflecting surface should be at a sufficient distance from the observer; when this is the case the reflected wave, having some distance to travel, is delayed, and is heard as an echo after the direct sound. The face of a cliff, or a high wall, such as the end of a building, usually forms a good reflecting surface.

The peculiarity of many echoes in repeating the last syllable, when various words or sentences are shouted, arises from the fact, that the reflecting surface is at such a distance that the reflected sound reaches the ear just one syllable behind the direct sound; the consequence is that all the reflected syllables, with the exception of the last, reach the ear along with the direct syllables, and are thus overpowered.

The distance at which the reflecting surface must be in order to render an echo distinct will depend upon the number of syllables that can be clearly uttered in a given time.

This is usually taken to be five per second. Then, as sound travels 224 feet in one-fifth of a second, it follows that if the reflecting surface be at the distance of 112 feet, one-fifth of a second will be taken up by the sound in going and returning, and consequently the reflected sound will arrive at the ear one syllable behind the direct sound. If the distance of the reflecting surface be double this, or 224 feet, then the echo will be heard to repeat two syllables; if 336 feet three syllables, and so on.

Echoes are termed monosyllabic, disyllabic, trisyllabic, and so on, according as they repeat one, two, three, or more of the terminal syllables of a word or sentence. The following device will explain a disyllabic echo—

Intervals of time,	1	2	3	4	5		
Direct sound,	*a*	*b*	*c*	*d*	*e*		
Reflected sound,			*a'*	*b'*	*c'*	*d'*	*e'*

The repeated syllables *a'*, *b'*, *c'*, are overpowered by *c*, *d*, *e*, while *d'*, *e'*, are distinctly heard. The letters bracketed arrive at the ear simultaneously, and the reflected sound being overpowered by the direct sound, is not therefore heard.

When there are two or more reflecting surfaces the same sound may be reflected backwards and forwards many times, and be heard after each reflexion. There are many places celebrated for multiple echoes of this kind; an echo in Woodstock Park, for instance, repeats seventeen syllables by day and twenty* by night.

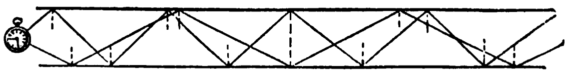


Fig. 8.—Reflexion of Sound by a Smooth Tube.

27. Reflexion of Sound by Tubes and Concave Surfaces.—Sound, in passing through a smooth tube, is repeatedly reflected from side to side, as shown in fig. 8. Besides being reflected in the manner indicated, the waves of sound are prevented from spreading, and hence the loudness or intensity of the sound is little impaired in passing along the tube.

* The reason why a greater number of syllables are heard by *night*, is that sound travels slower, owing to a decrease of temperature.

Hence the readiness with which sound is conveyed through tubes. Biot made a number of interesting experiments with the water-pipes at Paris, he found that the slightest whisper could be heard at the end of a pipe 3000 feet in length. He caused also a tune to be played at the end of such a pipe, whilst he listened attentively at the other end; he found that the tune, consisting as it did of sounds or notes of different pitch, conformed accurately to its natural measure, from which he very properly inferred that musical sounds of different pitch were transmitted with precisely the same velocity.

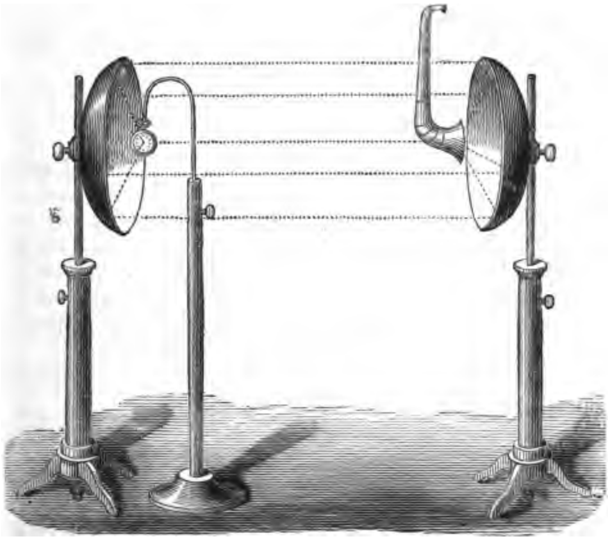


Fig. 9.—Reflexion of Sound by Concave Reflectors.

The use of tubes in factories and public buildings is of great service towards the ready communication of verbal messages between the different functionaries. In private dwellings also they are not uncommon. Each end of the tube is fitted with a plug in the form of a whistle, and when a message is to be given, for instance, from one of the public

rooms to the kitchen, the whistle is removed, the mouth is applied to the open end of the tube, and a stream of air is blown through, which, on reaching the other end of the tube, sounds the whistle there, and thus summons the servant to hear what is to be said. The message being communicated, the whistles are replaced.

The following experiment (fig. 9) is strikingly illustrative of the reflexion of sound by concave surfaces:—

A watch is placed in the principal focus of one of the reflectors, by which means the rays of sound are rendered parallel; these rays are received by the other reflector, placed exactly opposite the former, and at some distance from it. The ear being placed at the focus of the second reflector, or aided by an ear trumpet, readily distinguishes the ticks of the watch.

Concave walls and roofs in public buildings are often the source of considerable difficulty in rendering a speaker's voice distinctly audible in all parts of the building.

In one of the cathedrals in Sicily, mention is made of the confessional having been accidentally so placed that the whispers of the penitents were reflected by the curved roof, and brought to a focus in a distant part of the building. This focus was discovered one day by an individual who kept the secret to himself for some time, and who used to amuse himself by repairing to the spot, and thus hearing confessions which were intended only for the priest.

What are called "whispering galleries" owe their efficiency also to the reflexion of sound.

Fig. 10.—Speaking Trumpet.

The Speaking Trumpet (fig. 10), is a conical metallic tube, having at the small end a mouthpiece, and at the larger extremity a funnel-shaped enlargement termed the *bell.* By using this instrument a powerful voice can be heard at a great distance. The explanation of the action of

this instrument is that the waves of sound in passing through it undergo a series of reflexions, which are thereby prevented from spreading, and are thus adapted to reach some distance without much loss of intensity.

The Ear Trumpet (fig. 11) is made of various forms, but the general principle of their action is the same. They all taper more or less from the wide and open end, intended for the collection of the sound, to the smaller end which is placed in the ear. Waves of sound entering the funnel-shaped end are repeatedly reflected from side to side, the energy of the sound waves at the same time being concentrated upon a smaller and smaller bulk of air. It is of great service to those who are dull of hearing.

Fig. 11.—Ear Trumpet.

The Stethoscope (fig. 12), used so much amongst medical men, owes its action partly to the reflexion of sound, and partly also to the conduction of sound through the material itself. A practised ear can, by this instrument, discover at once anything abnormal in the sounds of the chest.

Fig. 12.—Stethoscope.

28. Deadening Sound.—In large halls where a speaker's voice would be rendered indistinct by reflexion, it is not an uncommon expedient to hang the walls with drapery—this, when done judiciously, serves the purpose well, the sound waves being thus absorbed. In the best constructed dwellings, architects are particular in forming the *partitions* between the different rooms. They are often made double with a clear air space between them. By this means the sound is so far deadened.

In the Pullman car now being introduced in the railways of this country, the flooring of the carriage is made double, the space between being filled up with sawdust. The clinking noise of the wheels upon the rails, even when the train

is going at an express speed, is thereby so subdued, that a conversation almost in a whisper can be kept up.

29. Refraction of Sound.—It follows from theory that when waves of sound are passing from one gaseous medium to another, of greater or less density, they should be refracted. Sondhauss showed that this refraction actually takes place by constructing lenses of films of collodion, and filling them with carbonic acid. Placing a watch on one side of a spherical or lenticular lens of this kind (fig. 13), and the ear on the other, a point will be found on the axis of the lens at which the ticking of the watch is much more distinctly heard than at any other point. The small india-rubber balloons sold as toys, when inflated with carbonic acid, make good sound lenses. The experiment requires some nicety in adjustment. It is more satisfactory when the watch and funnel are at such distances that the ticking of the watch is quite unheard except when the sound lens is in its position.

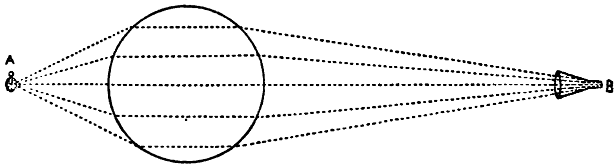


Fig. 13.—Refraction of Sound.

Very recently, investigations have been made as to the effect of the diminished temperature of the air upwards on the passage of sound; these seem to lead to the conclusion that the sound waves are lifted or refracted upwards by the atmosphere in proportion to the upward diminution of the temperaturé. There is little reason to doubt, therefore, that sound is capable of refraction.

30. Structure of the Ear—Auditory Range.—The human ear may be described as consisting of three parts—the *outer* ear, the *middle* ear, and the *labyrinth.* The accompanying diagram exhibits the different parts:—1—The *concha.* 2—The *meatus.* 3—The *tympanum* or *drum;* this closes the *outer* ear. 4, 5, 6, 7—A series of bones which transmit the impressions made on the tympanum, called respectively the *malleus, incus, os orbicularis,* and *stapes.* 8, 8—The *tympanic*

cavity or *middle* ear. 9—The *Eustachian tube,* leading into the back of the mouth, by which the air in the tympanic cavity is kept of the same density as that of the external atmosphere, giving the tympanum therefore perfect freedom of motion. 10, 10, 10—The *labyrinth,* so named from its complicated structure. It is filled with fluid, and over the lining membrane of it the terminal fibres of the auditory nerve are distributed. Between these nerve fibres are disposed very fine elastic bristles terminating in sharp points; and at another place, a multitude of minute fibres floating in the liquid, acting as sentries, to catch each the particular vibration to which it is appropriated, and transmit it to the nerve filaments.

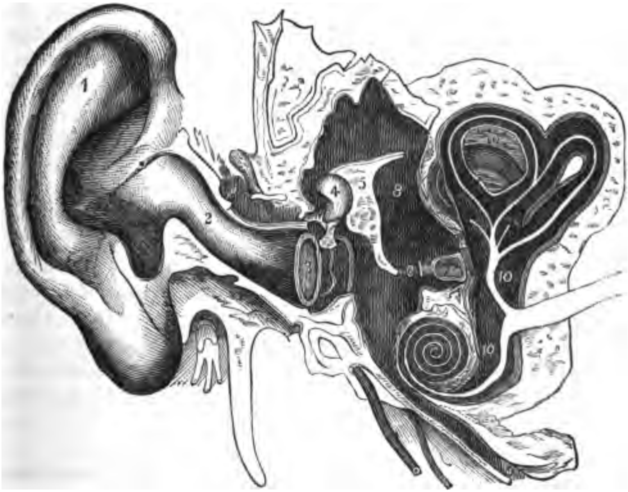


Fig. 14.—The Ear.

The sonorous waves, entering the outer ear, throw the tympanic membrane into a state of vibration. These vibrations are transmitted across the middle ear through the series of bones towards the labyrinth; there they affect the auditory nerve, and produce the sensation of hearing.

An ordinary musical ear can appreciate sounds arising

from 16 vibrations per second up to 38,000, that is, a range of about 11 octaves.* How is this accommodation of the organ effected? Looking to the anatomy of the tympanum, it appears that this adaptation to different rates of vibration is effected by means of slender muscles, which tighten or slacken the membrane according as the vibrations which fall upon it are quick or slow, thereby tuning it, as it were, to the proper discharge of its wonderful office.

31. Analytical Power of the Ear.—The ear possesses a remarkable power of analysing complex aërial waves, thus enabling us to perceive the elements of which they are compounded. It must be remembered that the aërial wave which reaches the ear at any moment is the summation of the individual systems of waves which are in course of propagation in the vicinity at the time. For instance, the sounds produced by an instrumental band in an orchestra are extremely various, but the aërial waves arising from each instrument, as a centre, are superposed, and arrive at the ear as a wave of great complexity. The ear, however, by its exquisite structure, analyses this intricate combination into simpler elements, and we are enabled easily to distinguish the sound of the violin from that of the clarionet, and the other instruments from these, and one from another.

32. Interference of Sonorous Waves.—If in two systems of sonorous waves condensation coincides with condensation, and rarefaction with rarefaction, the sound produced by each coincidence is louder than that produced by either system taken singly. But if the condensation of the one system coincides with the rarefaction of the other, a destruction total or partial of both systems is the consequence—a phenomenon which is called "Interference."

Let us illustrate this by reference to two vibrating rods giving the same pitch of note. One of these rods being sounded as in fig. 15 (*a*), the air is moulded into alternate condensations and rarefactions, indicated by the dark and light shading. If now the second rod be placed a *whole* wave-length in front of the first (*b*) and both be sounded, the condensations and rarefactions produced by the respective rods

* The practical range of musical sounds is from 40 to 4000 vibrations per second.

coincide, and the sound resulting from the coincidence is thereby intensified, as indicated by the deeper and lighter shading. But if the second rod be placed only *half* a wave-length from the other (*c*), then the condensations and rarefactions of the two systems of waves neutralise each other, and the air in front is brought to a state of rest; silence, therefore, is the consequence. The *total* extinction of sound, however, by the vibration of two sounding bodies, is not easily carried out by actual experiment.

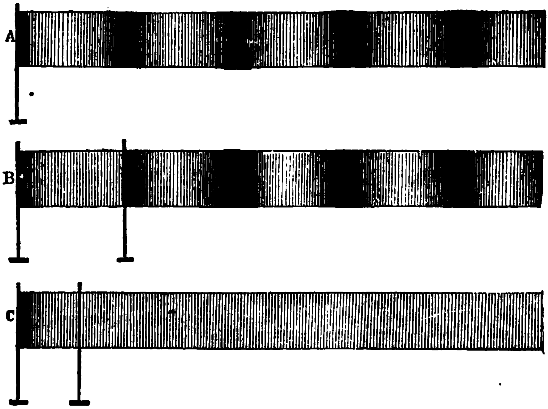


Fig. 15.—INTERFERENCE OF SOUND.

From the above explanation, it will be readily understood that interference can take place only when one system of waves follows another by an *odd* number of *half wave-lengths*. In the case of an *even* number, there is a reinforcement of the sound, consequent upon the coincidence of the condensations and rarefactions.

33. Mutual Interference of Prongs of a Tuning-fork.—During the vibration of a tuning-fork, the prongs alternately approach and recede from each other. During approach, the air is condensed between the prongs, giving rise to a condensed wave which is propagated in a direction at right angles to that in which the prongs vibrate, while the air outside the prongs is at the same time rarefied, giving rise to a rarefied

wave which is propagated *in* the direction in which the prongs vibrate. The adjacent condensed and rarefied waves, simultaneously produced, encroach upon each other, and interfere along four lines, proceeding from the prongs of the fork, as shown in fig. 16.

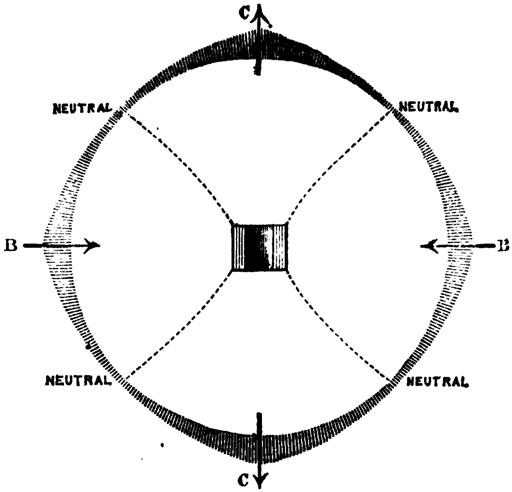


Fig. 16.—INTERFERENCE IN A TUNING-FORK.

C, C, are the condensations; and B, B, the rarefactions, on the approach of the prongs; these are reversed on the prongs receding from each other. The broken lines in the figure represent the lines all along which there is interference; they are hyperbolic curves.

34. Experimental Illustrations.—(1.) Take a tuning-fork, set it vibrating, hold it a few inches from the ear, and slowly turn it round. It will be observed that there are four positions of the fork in one revolution where the sound is inaudible, or nearly so. These positions are such that the ear falls in the lines of interference. (2.) Hold a vibrating tuning-fork over a resonant jar, and slowly turn it round; four positions will be observed in each revolution of the fork

when the jar ceases to resound. (3.) Holding the fork in such a position over the resonant jar that the latter ceases to resound, bring over one prong a small cylinder of paper, or a test tube, but without contact (fig. 17)—the jar will immediately resound. In this experiment, by cutting off the influence of one prong, the waves produced by the other are uninterfered with.

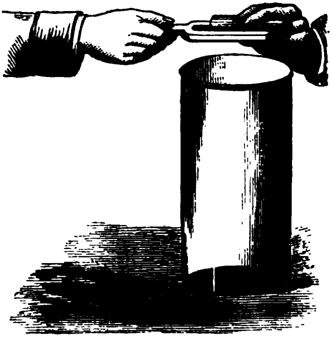


Fig. 17.—STOPPAGE OF ONE SYSTEM OF WAVES.

35. Interference in a Vibrating Disc. — When a disc vibrates (see Art. 62), adjacent sectors are in opposite phase of vibration, hence the waves they simultaneously produce are in opposite phase, and consequently interfere with each other. By holding a piece of pasteboard, cut as in the figure, over a disc vibrating with six divisions (fig. 18), half the sound will be shaded off, but the unshaded sectors will be in the same phase of vibration, and a considerable augmentation of the sound emitted by the plate is produced.

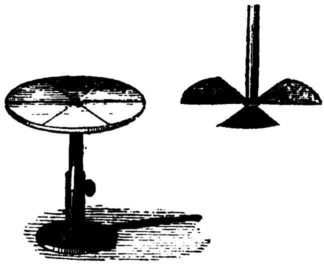


Fig. 18.—INTERFERENCE IN A VIBRATING DISC.

If a resonant cylinder is held opposite a nodal line in the vibrating disc, no increase of sound takes place, while the sound is considerably augmented when held near a segment. If, while the resonant cylinder is opposite a nodal line, half the sector is shaded off. the cylinder immediately resounds.

CHAPTER IV.

MUSICAL SOUNDS—DETERMINATION OF THE NUMBER OF VIBRATIONS.

36. Physical Difference between Music and Noise.—By a musical sound, in ordinary language, we mean a sound of definite pitch (highness or lowness), which remains audible for an appreciable interval of time without breach of continuity, during which interval the pitch is unchanged, and the intensity suffers no sudden changes. Other sounds than these we term noises, or simply sounds. Among common sounds, which have no claim to be considered musical, may be mentioned—the rustling of trees in the wind; the clatter of machinery; the sound produced when several adjacent keys of the piano are simultaneously struck.

The physical difference between a musical sound and a noise is simply this: *musical sounds* are the result of regular vibrations, which produce in the air a succession of waves exactly similar to each other. *Noises* are due to irregular vibrations, or a confused mixture of musical sounds, which produce aërial waves of great complexity and wanting in periodicity.

Fig. 19.—Simple Periodic Curve of a Musical Sound.

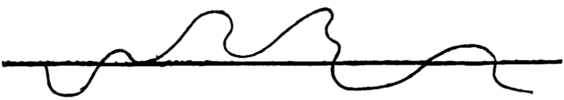


Fig. 20.—Complex Curve of a Noise.

In the case of a musical sound, the curve which we may take to represent the variations of pressure on the tympanic membrane is periodic, such as in fig. 19; while in the case of

a noise, the curve of pressure is complex and lacks periodicity, as in fig. 20.

37. Pitch, Intensity, and Quality of Musical Sounds.—There are three things which may be distinguished in regard to musical sounds—these are (1) *pitch,* (2) *intensity,* and (3) *quality.*

Pitch depends upon the *number of vibrations* executed per second; the greater the number of vibrations, the higher the pitch of the note. In connection with this point may be mentioned the fact, often observed no doubt, of the variation in the pitch of the locomotive whistle as an express train is *approaching to,* or *receding from,* a station. In the former case the number of vibrations which reach the ear in a given time increases, hence the pitch rises; in the latter case, that number decreases, hence the fall in pitch.

Intensity results from the *amplitude* of the vibrations or degree of disturbance given to the air particles. Thus, too notes of precisely the same pitch may have different degrees of loudness. Quality is the distinction which can be drawn between musical sounds, though of the samo pitch and intensity, when played on different instruments. Thus the quality of a violin is different from that of a flute, the quality of a flute from that of a clarionet, and so on. This peculiar difference is believed to arise from the number or character of the harmonics or overtones (see Art. 56) which are blended with the original notes.

38. Essential Conditions in the Production of a Musical Sound.—From what has just been said it will be seen that all that is necessary for the production of a musical sound is that a series of shocks be communicated to the air, and that these shocks be periodic and sufficiently rapid. Thus we shall see that, providing these conditions are fulfilled, musical sounds may be produced by a succession of taps or puffs, as well as by vibrations.

39. Production of Musical Sounds by Taps.—The production of musical sounds by taps is well shown by Savart's toothed-wheel apparatus. It is represented in fig. 21. The machine consists of two wheels, A and B, fixed in a wooden frame, the smaller having a certain number of teeth in the rim. They are so adjusted that B is made to revolve with

great rapidity, its teeth hitting upon a card E fixed near it. The number of revolutions is determined by reference to the *counter* attached to the axis at H. By turning the wheel A slowly at first the successive shocks of the teeth of the wheel B on the card are heard, and then gradually increasing the speed of revolution, the sound at last rises to a musical note which may be sustained at a certain pitch with a little care.

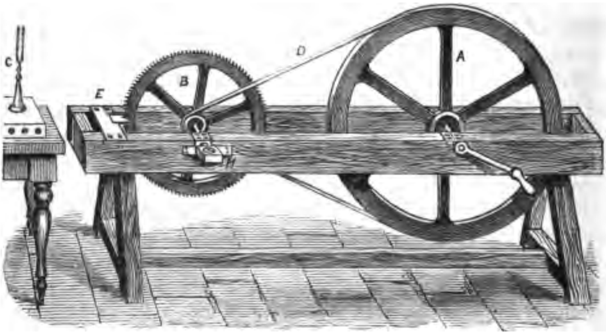


Fig. 21.—SAVART'S APPARATUS.

This apparatus is well adapted to determine the number of vibrations resulting from any musical note. The method of procedure will be understood by an example. The number of vibrations of a tuning-fork, C, mounted upon a sounding-box, is required. We should first sound the fork, and gradually increase the revolution of the wheel, B, until the note emitted by the card corresponds to that of the fork. We should then keep them in unison for a certain number of seconds, say ten. Now if we suppose that there are 100 teeth in the wheel, B, and that during the ten seconds the counter indicates fifty revolutions, we shall then have 5000 as the number of shocks or vibrations given to the card in that time. Hence 5000 divided by 10, or 500, will be the number of vibrations which the tuning-fork executes per second.

The instrument called a *rocker* (fig. 201), is capable of producing a very clear and pleasing musical note, which changes in pitch as the pressure applied to it varies. A quill

drawn rapidly along a file, or on the milled edge of a coin, may be made to produce also a musical sound of definite pitch.

40. Production of Musical Sounds by Puffs.—A puff of air suddenly escaping into the air produces a wave in it, and if a series of strong puffs are made to follow each other regularly, and with sufficient rapidity, they give rise to a musical sound. The most perfect instrument for the production of musical sounds in this way is the "Syren," so called from its capability of singing under water. It is the invention of Cagniard de Latour. The instrument is represented in fig. 22, with portions removed to show the construction.

A is a cylindrical brass case into which air is forced through the tube B. The top of this case C is perforated with a ring of holes bored obliquely—a plate D is placed directly above this, perforated in a similar manner, but the boring inclined in the opposite direction. This latter plate is made fast to a vertical stem, capable of turning freely in sockets. At the upper end of the stem there is a screw which engages a toothed wheel belonging to the *counting* apparatus, by means of which the number of revolutions of the plate D is recorded.

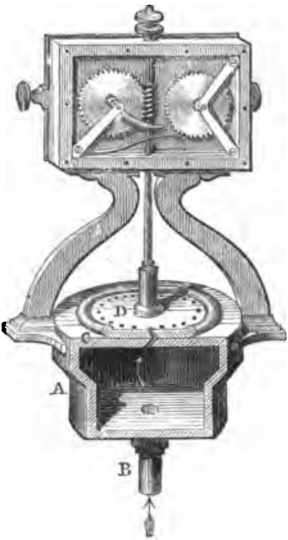


Fig. 22.—The Syren.

The action of the instrument is as follows: Air is forced into the tube B by means of an acoustic bellows, and entering the chamber under pressure makes its escape through the perforations in the fixed and movable plates. But by the device of having the holes bored obliquely, and inclined in opposite directions in the two plates, the air in its passage is made to turn the upper plate; the greater the blast of air the more rapidly the plate will rotate, and thus the more rapidly will the puffs

succeed each other. Therefore, by urging the air through the instrument with sufficient force, a note of any required pitch may be obtained, and, with proper control over the pressure of the air, may be maintained for any given time.

This instrument is also well adapted to the determination of the number of vibrations of a musical note. The method of procedure is the same as that already described. It has this advantage over the other method, that *unison* between the instrument and the sounding body can be more perfectly secured, and thus a more correct estimate of the number of vibrations can be obtained.

PHYSICAL CONSTITUTION OF MUSIC.

41. The Natural Scale of Music.—When any simple musical sound is heard, there is always a series of other sounds which naturally connect themselves with it, that is to say, these sounds when produced so affect our senses that we perceive they are related to the musical sound in question. When the notes forming the series are successively sounded in various orders, including the original sound, call the *key-note*, they give rise to sensations which are usually pleasant, while other sounds appear harsh and unpleasant.

The endless variety of melodies, tunes, and other kinds of music, are formed from certain sounds as key-notes, with their associated sounds variously and tastefully arranged.

Any musical sound selected as a key-note may, with its associated notes, be arranged in a series gradually rising in pitch. If this arrangement be made, and the notes successively sounded, beginning at the key-note, which we call 1, we perceive that each note produces a different mental effect, in addition to mere pitch, until we reach the 8th of the series, when the mental effect is the same as the 1st. Also the 9th note has the same effect as the 2nd, the 11th as the 3rd, and so on to the 16th, which affects us in the same way as the 8th. Thus the whole series of notes related to the key-note arrange themselves in a series of eights, or *octaves*, the eighth of one series being the first of the next.

The eighth note above or below any note in the series is said to be the *octave* of that note. The key-note, with its octave and six intermediate notes, is called *the natural musical scale*

or *gamut.* It is also known as the *major* or *diatonic* scale, and is universally adopted as the foundation of all music.

42. Names of the Notes.—The names given to the notes of the gamut by musicians are either letters or monosyllables as given below.

1st	2nd	3rd	4th	5th	6th	7th	8ve
C	D	E	F	G	A	B	C′
do	re	mi	fa	sol	la	si	do.

In reference to the fundamental note C, D is called the second, E the third, F the fourth, and so on. The octave (above) to C is usually marked C′, the octave to C′, C″, etc., and so with the other notes.

43. Mathematical relation of the Notes of the Scale.—The notes of the musical scale have a simple mathematical relation to each other. Taking as the key-note that produced by 24 vibrations per second, the other notes are produced by the following rates of vibration:—

1st	2nd	3rd	4th	5th	6th	7th	8ve
C	D	E	F	G	A	B	C′
24	27	30	32	36	40	45	48.

Taking the rate of C as 1, we have therefore the following ratios :—

$$1, \tfrac{9}{8}, \tfrac{5}{4}, \tfrac{4}{3}, \tfrac{3}{2}, \tfrac{5}{3}, \tfrac{15}{8}, 2,$$

The simple relation is at once apparent; the octave is produced by double the number of vibrations, the fifth by $\frac{3}{2}$, and so on.

44. Further Analysis of the Diatonic Scale.—The simplest relations in the notes of the scale are the ratios, 2, $\frac{3}{2}$, $\frac{4}{3}$, and $\frac{5}{4}$. The ratios $\frac{5}{3}$, $\frac{9}{8}$, and $\frac{15}{8}$, are not so simple when compared with the key-note, but are equally simple when compared with other notes of the scale.

The key-note, third, and fifth are in the ratio of 4 : 5 : 6. Three notes in this ratio are called a major triad. In the case given the key-note is called the *tonic*, and the triad the *tonic* triad. The *fifth* and *fourth* also bear major triads, and receive the names of *dominant* and *subdominant* respectively. Thus we have the three triads—

Tonic, ...	C : E : G	4 : 5 : 6
Dominant, ...	G : B : D′	4 : 5 : 6
Subdominant, . . .	F : A : C′	4 : 5 : 6

As these triads contain all the notes of the scale, the whole

diatonic scale may be regarded as made up of major triads. Commencing at F and taking the three triads in succession, all the notes are included thus—

F A C′ E′ G′ B′ D″.

45. Intervals.—The *interval* between two notes is the rise of one note above another. More strictly, it may be defined to be *the ratio between the rate of vibration of the higher note and that of the lower.* Thus if the rates of vibration of two notes are as 2 : 3, then $\frac{3}{2}$ is the interval between them.

The intervals therefore between the successive notes of the natural scale, can readily be calculated from Art. 43. They stand as follow:—

C		D		E		F		G		A		B		C′
	$\frac{9}{8}$		$\frac{10}{9}$		$\frac{16}{15}$		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{9}{8}$		$\frac{16}{15}$	
	T		T		S		T		T		T		S.	

It thus appears that there are but *three* intervals in the natural scale, expressed respectively by the fractions $\frac{9}{8}$, $\frac{10}{9}$, and $\frac{16}{15}$. The first two, from their differing so slightly from each other, are usually regarded as equal amongst musicians, and are called *major* tones (T); whilst the third is called a *semitone* (S). The order of tones and semitones is therefore as above.

46. Sharps and Flats.—The introduction of sharps and flats in music will now be readily understood. Their object is to secure the natural succession of tones and semitones, whatever note is taken as the fundamental or key-note. The following examples are sufficiently illustrative:—

(1.) KEY OF D.

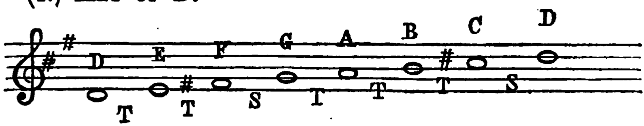


Fig. 23.—KEY OF D.

Here between E and F, according to our *model* scale, there is naturally a semitone; F, therefore, must be raised half a tone, or sharpened. Again, between B and C there is a semitone—C must therefore also be sharpened. Hence in the scale of D there must be *two* sharps introduced to preserve

the natural order of tones and semitones. Instead of putting the sharps before the particular notes as they occur, they are commonly put at the beginning of the clef, as in the diagram.

(2.) KEY OF E FLAT.

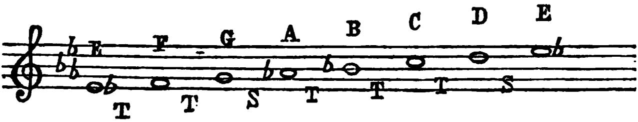


Fig. 24.—KEY OF E FLAT.

Here the note E is depressed half a tone, or flattened. The interval therefore between E flat and F is the proper one—a tone. Between G and A there is naturally a tone, but a semitone is required, therefore A must be flattened—between A flat and B there is a tone and a half—B therefore must be flattened. B being thus flattened, there is between B flat and C the proper interval. Thus in the key of E flat, we are compelled to introduce *three* flats to keep up the necessary succession of tones and semitones.

47. Beats.—What are called *beats* in music are due to the alternate coincidence and interference of two systems of sonorous waves. Let us suppose that two sonorous bodies, whose periods of vibration slightly differ, emit sound together. At first their effects conspire; in other words, the condensations and rarefactions which they separately produce in the air coincide, causing an increase in the sound; but after a short time the condensation produced by the one body encounters the rarefaction produced by the other, and there results a mutual interference, which causes a partial destruction of the sound. Coincidence sets in a second time, to be followed by another interference, and so on. Thus, whilst the bodies continue sounding, there will be an alternate increase and diminution of the sound, caused by the coalescence and interference of the vibrations respectively; it is these alternations of loudness and faintness that get the name of "beats."

The number of beats which take place in a second is always equal to the *difference between the number of vibrations* of the sonorous bodies. This will appear from the

following example:—Suppose two tuning-forks to make, respectively, 200 and 210 vibrations per second; sound them together. In the interval required for the one fork to execute one vibration more than the other, that is in $\frac{1}{10}$th of a second, whilst one gives 21 vibrations to the other's 20, it is clear that *one* beat must occur; but in the case in question there are ten such intervals, therefore there must be 10 beats per second, *i.e.*, $210 - 200 = 10$ beats.

48. Experimental Illustrations of Beats.—(1). Take two tuning-forks of the same pitch, and load one of them with wax, strike them and hold them over a resonant jar; the beats are rendered very perceptible. The addition of the wax reduces the number of vibrations. The same thing may be effected by heating one of the forks.

(2). Adjust two *singing* flames as in fig. 25. When a jet of coal or any combustible gas is made to burn within a tube, a musical note may be elicited. The flutter produced by the escape of gas from the burner sets the air in the tube into a state of vibration; the air then reacts upon the flame, and governs it in a manner similar to what obtains in an organ pipe (Art. 65). By taking two such tubes, and providing one with a paper slider, they may be tuned in perfect unison. By raising or depressing the slider, the tubes are varied in length, and beats are produced. In this experiment, the flames are seen to dance as the beats occur.

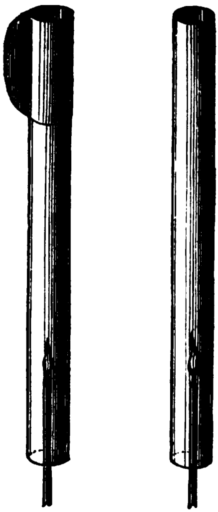


Fig. 25.—Beats with Singing Flames.

(3). On a piano or harmonium strike a *low* note and its sharp together; the beats are heard with great distinctness, much more so than when a *high* note and its sharp are sounded, because of the vibrations being slower.

(4). Another excellent illustration is afforded by the "Burmese gong," shown in fig. 26. Whilst the string is twisted, let the gong be struck; the string tending

to unwind itself causes the gong to rotate, and in consequence of this motion, beats are evolved with striking force.

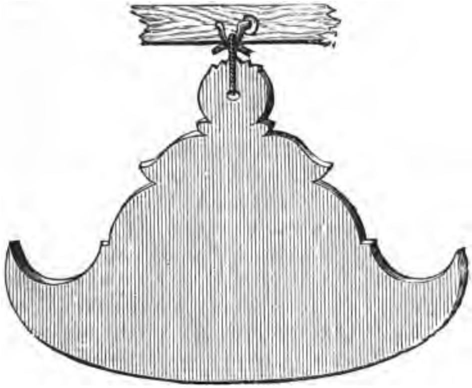


Fig. 26.—"BURMESE" GONG.

49. Consonance and Dissonance—Helmholtz's Theory.—When notes are sounded together, so as to give a pleasing effect to the ear, they are said to produce *concord;* if the opposite effect take place, they produce *discord.* These opposite auditory sensations are due to the absence or presence of strong and rapid beats. The most perfect concord of two tones results from a note and its octave—here the coincidence or interference of the vibrations is very frequent, for whilst the one note performs one vibration, the octave performs two—and thus there are no beats perceptible. On the other hand, a most unpleasant discord is produced by two notes differing by a semitone—in this case there is great infrequency in the coincidence or interference of the vibrations—and the beats become very marked.

On this subject Helmholtz remarks:—"As long as no more than four to six beats occur in a second, the ear readily distinguishes the alternate reinforcements of the tone. If the beats are more rapid, the tone grates on the ear, or if it is high, becomes cutting. . . . *Roughness* of tone is the essential character of dissonance. When the number of beats is

at the rate of 33 per second, the dissonance is at a maximum; at 100, the roughness is still discernible; and at 132 it totally disappears. . . . Even when the fundamental tones have such widely different pitches that they cannot produce audible beats, the upper partial tones (overtones) may beat and make the tone rough."

This theory is found to be in complete accordance with observed facts. Thus if we take, say, the middle C of the piano, which gives 256 vibrations per second, and sound along with it its higher octave C′, we have 512 – 256, or 256 beats per second, and there is no perception of roughness. If, now, we sound together C and G, we get 384 – 256, or 128 beats, a number just on the verge of 132, and the roughness, if at all discernible to delicate ears, is very slight. Again, if we sound C and F, we have 340 – 256, or 84 beats, and now the roughness becomes quite sensible. Lastly, we sound C and E, we have then 320 – 256, or 64 beats, and the roughness is more perceptible.

The combinations here specified are, respectively, those of (1) a note and its octave; (2) a note and its fifth; (3) a note and its fourth; and (4) a note and its third (major). It appears, therefore, that those combinations *whose ratios are represented by small whole numbers*, are those which give the most perfect harmony (see Art. 44).

50. Combinational or Resultant Tones.—It is found that, under certain circumstances, when two notes are sounded together, tones differing from either of the primaries are heard. These are termed *combinational* or *resultant* tones. They are of two kinds—(1) *difference tones*, and (2) *summation tones*, so called from the fact that the former has a period of vibration equal to the difference between the periods of vibration of the two primaries, and the latter a period equal to their sum.

Tyndall recommends the use of two singing flames similar to those in fig. 25, to render difference tones audible. The union of a note and its fifth gives rise to a tone an octave below the lower of the two notes; of a note and its fourth a twelfth below; and of a note and its third (major) two octaves.

Helmholtz, to whom the discovery of summation tones is due, proved mathematically that such tones must necessarily

result from the recognised laws of dynamics as applied to the mutual action of two systems of waves traversing the same mass of air.

Combinational tones may also, by suitable means, be made to produce beats.

51. Sympathetic Vibration.—It is not uncommon to observe, when one is singing in a room, a kind of response from one or other of the gas globes—a vibration occurring when certain notes are sung. Indeed, a thin bell-glass has been known to be broken by a singer's voice. Or again, on sounding a shrill whistle near a piano, certain of the wires seem to respond, and catch the note of the particular pitch. Such effects are due to what is called "sympathetic vibration." The vibrations of the disturbing body, in such cases, *coalesce* with the vibrations of the other body, and in virtue of the successive shocks of the aërial agitations upon it, that body becomes eventually disturbed, and vibrates in unison along with it. The following experiment is strikingly illustrative of this fact: A number of tuning-forks of different pitch are mounted on sounding-boxes. A tuning-fork, whose period of vibration is the same as that of one of them, is placed near them and agitated; after a short time let it be silenced; it will be found that all the forks remain quiescent and unaffected, except *the one* whose period of vibration synchronises with the one originally disturbed—that one alone is thrown into vibration.

CHAPTER V.

TRANSVERSE VIBRATION OF STRINGS.

52. Stationary Waves.—A wave is said to be *stationary* when its form alternately changes from that of a crest to that of a hollow, but does not to the eye exhibit any progressive movement. Waves of this kind are easily produced by the superposition of direct and reflected waves on a stretched cord. For this purpose, a vulcanised rubber tube, 15 or 20 feet long, containing a coil of wire, or filled with sand, answers very well. One end of the tube should be fixed at such a height as to allow it to hang vertically, or nearly so. If the free end of the tube is taken in the hand, and quickly shaken, a wave is produced on the tube which proceeds along the tube to the end, is there reflected, and returns to the hand. By carefully timing the impulses given to the tube by the hand, a series of waves of the same length may be made to follow each other on the tube. In order to produce stationary waves on the tube, it is not only necessary that they should follow each other regularly, but that the length of each half wave should be exactly an aliquot part of the length of the tube, such as $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and so on.

When the tube is made to vibrate as a whole, the length of wave generated must be regarded as equal to half the length of the tube, inasmuch as the wave is continually reflected at one fixed end and the other, and this constitutes the ordinary *transverse* vibration of the tube.

To produce a wave on the tube, the length of which shall be equal to the length of the tube, it is only necessary to shake the tube as fast again as when required to make it vibrate in the ordinary way. The effect of causing two half wave-lengths exactly to extend along the tube, is that the direct waves and reflected waves will at all times completely interfere with each

other at the middle point of the tube. For at the same moment that the direct wave leaves the hand, a reflected wave in opposite phase starts from the fixed end, and the consequence is, that corresponding points in the two waves arrive in opposite phase at the middle point of the tube at the same moment, and keep it at rest. The appearance of the tube presented to the eye is that of its two halves vibrating independently of each other, the middle point being at rest. The point where no motion is perceptible is called a *node*, and the vibrating parts, *loops*, or *vibrating segments*.

53. Sonometer—Sound-boards—Resonance.—This instrument is represented in fig. 27. It is adapted to prove the laws which regulate the transverse vibration of strings, as well as to illustrate the vibration of a string in so many parts.

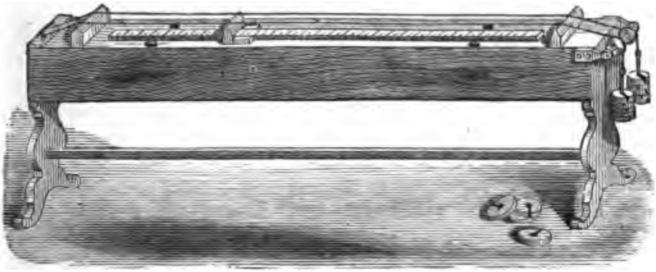


Fig. 27.—SONOMETER.

The amount of motion communicated by a vibrating string to the air being too small to be perceived as sound, even at a small distance, it is necessary to connect the string with surfaces of larger area, which are capable of taking up the vibrations and transferring them to the surrounding air, hence the object of mounting the strings as in the figure. The vibrations of either string are thus communicated through the bridges to the sounding-box beneath; this large surface partaking of the vibrations causes an increased disturbance in the air, and thus the sound is much enforced.

Many of our musical instruments, such as the harp, the guitar, the piano, the violin, owe their richness and fullness of tone to the same cause. This effect is known as *resonance*.

54. Laws of Vibrating Strings.—The transverse vibration of strings is dependent upon four things, viz.: length, thickness, tension, and density. Accordingly, there are four laws which regulate such vibrations. They are as follow:—

I. The rate of vibration is *inversely* proportional to the length. Thus—

Length,	1	2	3	4	$\frac{1}{2}$
Rate,	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	2

II. The rate of vibration is *inversely* proportional to the diameter or thickness. Thus—

Diameter,	1	2	3	4	$\frac{1}{2}$
Rate,	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	2

III. The rate of vibration is *directly* proportional to the square root of the stretching weight or tension. Thus—

Tension,	1	4	9	16
Rate,	1	2	3	4

IV. The rate of vibration is *inversely* proportional to the square root of the density. Thus—

Density,	1	4	9	16
Rate,	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$

These laws may be all verified experimentally by the sonometer.

55. Formation of Nodes and Loops on a Stretched String.—If a musical string is slightly touched or *damped*, as it is called, at a point one-half, one-third, one-fourth, etc., of its length, and the shorter segment agitated by a fiddle bow, the whole string will immediately vibrate in two, three, four, etc., equal parts, separated from each other by nodes.

The rate of vibration of each segment will, obeying the first law, be inversely as its length.

Thus, if damped at one half, the string vibrates as in fig. 28.

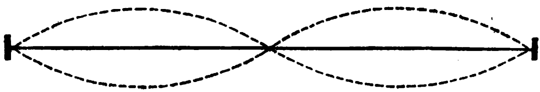


Fig. 28.—String with One Node.

The rate is twice that of the whole string, and consequently the musical note is an octave above the fundamental.

If damped at one third, the string vibrates as in fig. 29; the note generated being the twelfth above the fundamental.

Fig. 29.—STRING WITH TWO NODES.

The existence of the nodes and ventral segments may be well shown by placing small pieces of cardboard or riders of the form (Λ) across the wire, when those placed on the vibrating segments will be thrown off, those on the nodes remaining comparatively unaffected.

56. Harmonics or Overtones—Eolian Harp.—When a string vibrates as a whole, it usually divides at the same time into its aliquot parts; smaller vibrations are superposed upon the larger, the tones corresponding to these smaller vibrations, mingling at the same time with the fundamental tone of the string. These additional tones are called *harmonics* or *overtones*. In short strings they cannot be detected except by delicate ears, but in a long string, say of 32 feet, suitably mounted, several of them can be readily distinguished, especially when the fundamental tone is dying away. By touching lightly different parts of a string of the sonometer, so as to obtain the aliquot parts, and sounding these with a fiddle bow, the successive harmonics may be elicited and thus rendered audible separately. Suppose the fundamental tone to be C, the notes corresponding to the several harmonics will stand thus—

		HARMONICS.							
Tones—Fundamental......		1st	2nd	3rd	4th	5th	6th	7th	&c.
Length of String.......	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{6}$	$\frac{1}{7}$	$\frac{1}{8}$	...
Note......................	C	C′	G′	C″	F″	G″	A″/B″	C‴	...

The sixth harmonic is a note *between* A″ and B″.

When any point of a string is struck, all the higher harmonics which *require that point for a node* disappear. Thus, if a string of the sonometer be plucked at its middle point, its *first* overtone is absent, for if the string be damped at that point no octave is heard. Along with the octave all the harmonics, whose rates of vibration are any *even* number of times the rate of the fundamental tone, also vanish, for these require also a node at the centre.

In a piano the strings are so arranged that the hammers strike them at such points as to avoid calling forth any other than the more *consonant* overtones. By this artifice the most pleasing effect is produced.

We have overtones not only from strings but from most other sonorous bodies. Our different musical instruments manifest more or less the production of overtones. It is in fact *the addition of such overtones* to the fundamental tones of the same pitch which enables us to distinguish the sound of one musical instrument from that of another. The *quality* or *clangtint* of musical sounds, as elicited from different instruments, is thus determined by the number or character of the overtones which are blended with the fundamental tones.

The *Eolian harp* owes its action to the blending of harmonics. It consists of suitably stretched strings, mounted upon a sounding-box. The instrument is placed between the sash and frame of a window, so as not to allow of the entrance of the outer air, except over the strings. The air-currents thus made to act on the strings set them vibrating, and there is produced a variety of pleasing combinations of notes.

57. Longitudinal Vibration of Strings.—A musical note may be elicited from a string vibrating longitudinally. For this purpose the string is rubbed with resined leather. The note thus obtained is much higher than when the string vibrates transversely, the reason obviously being that, owing to the rigidity of the wire, the pulse moves with great velocity from end to end. It is found that the rate of vibration is *inversely proportional to the length*, and is *independent* of the tension.

The comparative velocity of sound through wires of different material may be found experimentally in this way:—If the lengths, for example, of the wires which give the same pitch of note be determined, these lengths will express the relative velocities.

58. Transverse Vibration of Rods.—Three cases fall to be considered:—

(1.) A rod fixed at *both* ends can vibrate as a whole, and also in segments separated by nodes. The nodes divide the rod into aliquot parts as in the case of a string, but the rates

and succession of tones are different. The rates of vibration (commencing with the fundamental tone) are proportional to the *squares* of the numbers 3, 5, 7, etc.

(2.) A rod fixed at *one* end may vibrate as a whole and in segments, as shown in fig. 30.

Here the rates of the successive *overtones* are as the squares of 3, 5, 7, etc., whilst the rate of the fundamental tone is to the rate of the first overtone, as the square of 2 to the square of 5.

In regard to rods of different lengths, it is found that the rate of vibration of the fundamental tone is *inversely proportional to the square* of the length.

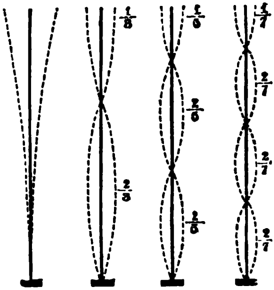


Fig. 30—SUBDIVISION OF ROD FIXED AT ONE END.

Tones—Fund. 1st ov. 2nd 3rd

Rates $\begin{cases} 2^2 : 5^2 \\ 3^2 : 5^2 : 7^2 \end{cases}$

The *musical box* is constructed on this principle. It consists of a series of metallic strips or tongues acted upon by a revolving cylinder, pierced with a number of protruding pins, which, being properly adjusted, throw the necessary tongues into vibration, and thus produce the tune. The revolving cylinder can be shifted so as to change the melody.

(3.) A rod free at *both* ends, but supported near the ends at equal distances, when struck in the middle gives its fundamental tone. The points of support are necessarily nodes, but the intervening part of the rod may be made to vibrate as a whole, and also in segments. The succession of tones is the same as in a rod fixed at both ends.

The *claque-bois* acts on this principle: it consists of pieces of hard wood of such dimensions as to yield the notes of the natural scale, strung along a cord which passes near both ends. The same principle is carried out also in the *glass harmonica*, which consist of strips of glass instead of wood.

59. Longitudinal Vibration of Rods.—(1.) A rod fixed at *both* ends divides itself in the same manner as a wire (see Art. 55).

(2.) A rod fixed at *one* end, when sounding its fundamental tone, vibrates only half as fast as a rod of the same length

fixed at both ends. The mode of division is the same. The order of tones is proportional to the odd numbers, 1, 3, 5, etc.

(3.) A rod *free* at both ends gives its fundamental tone when clamped in the centre. But by clamping it at suitable points it may be made to subdivide itself, the rates of vibration of the successive tones being proportional to the natural numbers 1, 2, 3, 4, etc. The rate of vibration of the fundamental tone of a rod free at both ends is therefore the same as the rate of that of a rod of the same length fixed at both ends. The wave-length of the fundamental note is found to be *double* the length of the rod. In the case of a rod fixed at one end, the wave-length of the fundamental note is therefore *quadruple* the length.

60. Velocity of Sound in Rods.—The vibration of the air in an open organ pipe is executed in precisely the same way as that *of a rod free at both ends vibrating longitudinally* (see Art. 64), hence an easy method of finding the velocity of sound in rods of different material. Thus, for example, we have only to find the length of the rod vibrating in this way which gives the same note as an open pipe of a given length, and knowing the velocity of sound in air, we have only to multiply this by the length of rod thus determined.

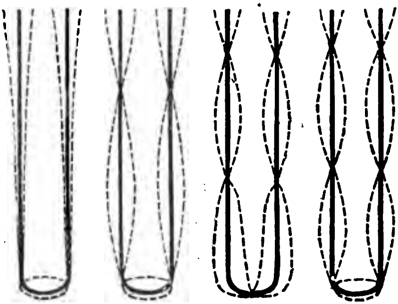


Fig. 31.—Vibrations possible in a Tuning-fork.

Tones—	Fund.	1st ov.	2nd	3rd.
Nodes	2	4	5	6
Rates	2^2 ·	5^2		
		3^2 :	5^2 :	7^2.

61. Vibrations of a Tuning-fork.—When a tuning-fork emits its fundamental tone, there is a node at the base of each prong. The tuning-fork is capable of other divisions, as exhibited in fig. 31.

The succession of tones, therefore, is the same as in a rod free at *one* end, but the nodes are different.

Chladni determined this division of a tuning-fork by strewing sand over the fork before making it vibrate.

62. Vibration of Plates.—(1.) *Square plates.*—A square plate clamped at its centre emits its deepest or fundamental note when a bow is drawn across the edge close to one of the angles. The plate then divides itself by nodal lines, as in fig. 32 (1). These may be made manifest by fixing the plate in a horizontal position and strewing sand on it; the sand being tossed from the vibrating parts, collects along the nodal lines.

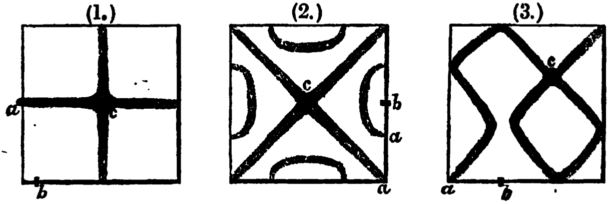


Fig. 32.—Division of Square Plates.

Many other figures, some of great beauty, may be produced by variously clamping and agitating the plate. Figures (2), (3), represent specimens; in each case the letter *a* indicates the point where the plate is damped, *b* the point along which the bow is drawn, and *c* where the plate is fixed. Such figures were first obtained by Chladni, and are hence known as "Chladni's figures."

(2.) *Circular plates.*—A circular plate, when clamped at the centre and caused to yield its fundamental note, divides itself into four vibrating parts, separated by four radial nodal lines.

By touching the edge in certain places while putting it into vibration, other radial lines may be produced. Fig. 33 shows the points at which the plate ought to be damped and agitated so as to produce the particular modes of division.

The letters indicate the same as before. The rates of vibration are found to be *directly proportional to the squares of the number of sectors* into which the plate is divided. Thus the rates in the above cases will be as the squares of 2, 3, 4. The number of sectors is in all cases an *even* number.

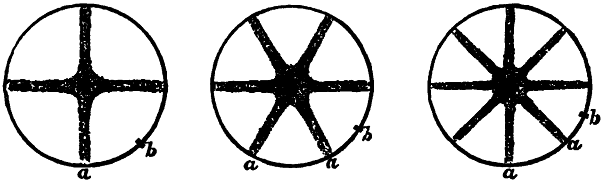


Fig. 33.—Division of Discs.

When a disc emits its fundamental note, the rate of vibration is *directly* proportional to its thickness and *inversely* proportional to the square of its diameter. Thus let A, B, and C be three discs of the same material, B double as thick as A, but of the same diameter, and C half the diameter of A, but of the same thickness, the rates of vibration will be as 1, 2, and 4, that is, B will give the octave to A, and C the double octave.

63. Vibration of Bells.—When a bell rings or sounds it divides itself into four vibrating portions separated by nodal lines which run up from the bottom of the bell and converge towards the top. Fig. 34 shows the manner of vibration. The continuous circle representing the rim of the bell in a state of rest—when the hammer or tongue strikes the side, the rim changes to a sensible ellipse or oval, but owing to the elasticity of the material it recovers itself, and goes too far in the opposite direction. The vibrations of the bell thus consist in alternate changes from one configuration to another, as indicated by the dotted curves, nd the intersection of these ovals gives rise to the nodal

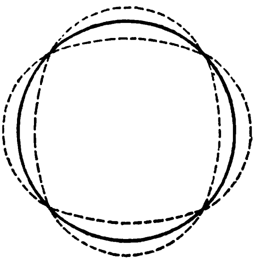


Fig. 34.—Division of Bells.

lines. By damping proper points a bell is capable of the same subdivision as a circular disc, the succession of its tones being also similar.

One of the most remarkable bells in the world is found in China, at the "Temple of the Great Bell." It measures 16 feet in height, has a diameter of 10½ feet at its widest part, and is decorated over its outer surface with 810,000 characters or designs. It is believed to have been cast as early as the year 1400. The tone is said to be exceedingly rich and mellow.

Helmholtz remarks "that the art of the bell-founder consists precisely in giving bells such a form that the deeper and stronger partial tones shall be in harmony with the fundamental tone, as otherwise the bell would be unmusical, tinkling like a kettle. The higher partial tones are always out of harmony, and hence bells are unfitted for artistic music."

The overtones of rods, plates, and bells, have not the simple ratios to the fundamental tones that the overtones of strings have, and are not, therefore, *harmonic* tones; hence such sounding bodies are employed in music only to a very limited extent.

Experimental Illustration.—The mode of vibration of a bell is strikingly illustrated in the following way:—Take a common bell-glass tumbler, fill it about two-thirds full of water, and throw it into vibration either by drawing the wet finger over its edge or by using a bow. The vibrations of the glass are communicated to the liquid, and the surface becomes covered with beautiful ripples which are seen to proceed from the four vibrating segments.

CHAPTER VI.

64. Vibration of Columns of Air.—We have now to look at the vibration of gaseous columns.

The simplest method of exciting vibration in a column of air is by means of resonance. Thus if we take a vibrating tuning-fork and hold it over the mouth of a jar, as in fig. 35, we have the sound of the fork enforced. The height of the column which most readily responds to the fork, in other words which gives the *maximum* resonance, is found to be one-fourth of the wave-length of the fork. This height can be easily determined experimentally for any fork by taking a sufficiently tall jar and shortening the aërial column gradually by pouring water into the jar. By a little care the column, whose period of vibration perfectly corresponds with that of the fork, can be obtained. In such cases the *material* enclosing the column has no effect on the pitch of the note, that is, the sound does not proceed from the vibration of the vessel, though the hand placed on its side may feel a sensible tremor, but alone from the vibration of the enclosed air.

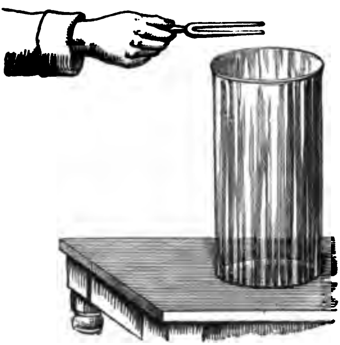


Fig. 35.—Resonant Jar.

How does the motion of the air-particles take place? To understand this, let us take the case of a tube open at both ends. Let A represent the tube (fig. 36), with the air in a state of rest, and let the different air-particles be indicated by vertical lines at equal distances from each other.

When the air in the tube is made to vibrate, all the particles begin to move longitudinally at the same instant *except* the one in the centre—the particles from both halves of the tube in their approach to the centre move over unequal spaces, those at the ends move over the greatest spaces, and those towards the middle the least. The result is a condensation of the whole air in the tube; that condensation, however, being least at the ends, and gradually increasing towards the centre, where it is a maximum. This is indicated in B by the varying distances of the vertical lines. Thereafter the particles of air tend to recover their position of equilibrium, but in doing so they move too far in the opposite direction, that is, the air-particles from both halves of the tube recede from the centre towards the ends, moving as before over unequal spaces, diminishing now from the centre outwards.

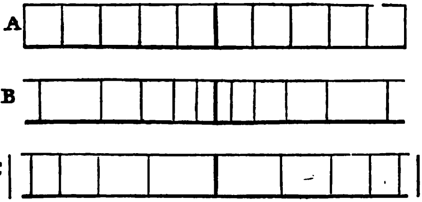


Fig. 36.—Mode of Vibration of an Air-column.

This causes a rarefaction of the air in the tube, the rarefaction being greatest at the centre, and least at the ends. The disposition of the lines in C shows this. Condensation again ensues, to be succeeded by another rarefaction, and so on alternately. It appears, therefore, that whilst there is no vibration in the *centre* of the tube, the air in the immediate vicinity on either side of it undergoes rapid alternations of density; at the ends of the tube, on the other hand, these being open to the external air, there is no sensible change of density.

The centre of the tube we may therefore call a node, and each end the middle of a ventral segment. In a tube closed at one end, the closed end is necessarily a node, whilst the open end is the middle of a ventral segment. Such being the case, an open tube may be regarded as two closed tubes

set base to base. The note, therefore, from an open tube of a certain length is the same in pitch as that from a closed tube of half that length, or, which is the same thing, the note from an open tube of a certain length is the octave to that from a closed tube of the same length. We can hence determine the *wave-length* of the note emitted by a stopped or open pipe. In the former case, the wave-length is *four times* the length of the pipe, and in the latter case *twice*.

65. Organ Pipes.—The manner in which the column of air is made to vibrate in an organ pipe will be understood from fig. 37.

The air, urged through the tube A, is led through the narrow passage A B, and made to play upon the thin edge of the pipe at the *embouchure* C. It produces there a kind of flutter, some pulse of which is raised by the resonance of the aërial column inside to a musical sound, and thus the pipe "speaks." In an open pipe there is a flexible metallic tongue, which, by being moved up or down, serves the purpose of tuning it. In a stopped pipe there is a plug or piston at the top, which may be moved out or in.

The air in the pipe may be made to vibrate by taking a tuning-fork of the same period of vibration as that of the aërial column and holding it opposite the embouchure.

66. Overtones in Organ Pipes.—Both open and stopped pipes are susceptible of other modes of division by nodes, giving rise to overtones.

Fig. 37.—Organ Pipe.

Figs. 38, 39 exhibit the position of the nodes (indicated by the small dotted lines), in the two kinds of pipes, when the first three harmonics are elicited. The fractions show the exact divisions of the aërial columns. In an open pipe the rates of vibration of the successive notes (including the fundamental), are as the numbers 1, 2, 3, 4, etc.

In a stopped pipe the rates are proportional to the odd numbers 1, 3, 5, 7, etc.

67. Experimental Illustration of Nodes and Loops.—

One of the most striking illustrations of the existence of nodes and loops in an organ pipe is afforded by the following experiment: Take a pipe (fig. 40), furnished with three apertures at equal distances, dividing the whole into four equal parts, each aperture being fitted with a small cover. Let all the apertures be at first closed. When the fundamental note is sounded, there is a node, as we have seen, at the centre, where there are constant changes of density. If now the cover of the central aperture be opened, a node is rendered no longer possible at this point, seeing that it is exposed to the external air; the consequence is that the note is at once affected. Should the first harmonic be sounded whilst the apertures are closed, then the opening of the central cover will not affect the note, for that point is then the middle of a ventral segment.

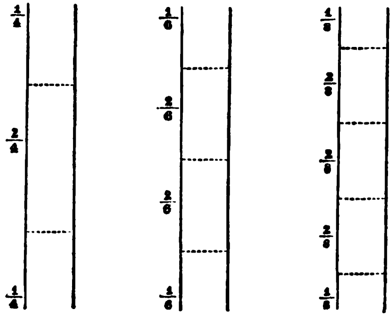


Fig. 38.—SUBDIVISION OF AN OPEN PIPE.

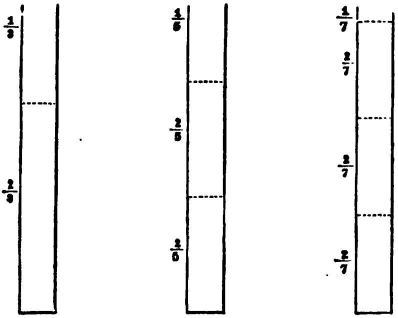


Fig. 39.—SUBDIVISION OF A STOPPED PIPE.

From this experiment we can understand the change of notes which takes place by fingering in the common flute.

That the air in an open pipe, when a note is sounded, does not go *through* the pipe may be very simply proved by placing the pipe in a horizontal position with the embouchure vertical, and placing two candles, one opposite the embouchure, and the other at the end of the pipe, the former is at once extin-

Fig. 40.

guished, whilst the latter is observed only to flicker.

68. Reeds.—These are small tongues of flexible material which vibrate to and fro in a rectangular orifice (fig. 41). The orifice being alternately opened and closed, the air escapes in puffs, which, occurring at regular periodic intervals, give rise to the sound. The pitch of the note depends upon the rate of vibration of the reed. We have examples of reed instruments in the harmonium, concertina, reed organ-pipes, Jew's-harp, clarionet.

69. The Human Voice—Vowel Sounds.—The organ of voice is called the *larynx*—it is the upper part of the windpipe. The windpipe, in opening into the larynx, tapers towards the top, and terminates in a small slit, called the *glottis* (fig. 42). The membranes enclosing the glottis are acted upon by elastic bands, called the *vocal chords*, which are relaxed or tightened at will. There is a flap or lid, termed the *epiglottis*, which accurately covers the glottis. The food, in its passage into the gullet, presses upon this lid and keeps it close upon the aperture until the food has passed; when, from its elasticity, it rises and allows respiration to go on. When we are breathing, but not speaking, the membranes of the glottis are in a state of relaxation, and the air in its exit from the lungs has too little force to cause them to vibrate; in these circumstances there is no sound, no voice. When we wish to speak, no sooner does the volition exist than the vocal chords brace up the membranes to the

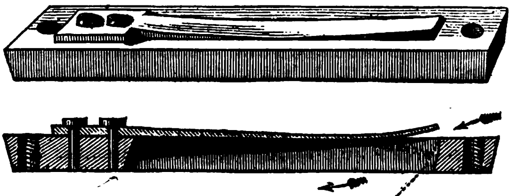


Fig. 41.—The Reed.

necessary tension; the lungs then doing their duty send a blast of air through the glottis, throw the membranes into vibration, and thus sound or voice is produced.

It will thus be seen that the voice results from the vocal chords as they vibrate, alternately opening and closing the glottis, so that the air is made to escape in a series of puffs; it is these puffs succeeding each other in rapid succession which give rise to the sound of the voice, just as the puffs of the syren produce musical notes. The vocal chords therefore act like a reed. While a person is singing, his vocal chords undergo rapid changes in tension, being tightly stretched for high notes, and less so for lower notes.

Fig. 42.—The Vocal Organs.

Speech is voice modulated by the throat, tongue, and lips. In uttering the different *vowels* a definite position of the mouth is required for each vowel, and the cavity of the mouth performs the important office of strengthening or giving prominence to that particular tone which characterises each vowel sound. The human voice is rich in overtones.

"Through the agency of the mouth we can mix together the fundamental tone and the overtones of the voice in different proportions, and the different vowel sounds are due to different admixtures of this kind. I have here a series of tuning-forks, one of which I strike, and placing it before my mouth, adjust the size of that cavity until it resounds forcibly to the fork. When this is done, I remove the fork, and without altering in the least the shape or size of my mouth, I urge air through the glottis, I obtain the vowel sound *u* (*oo* in hoop), and no other. I take another fork, strike it, place it in front of the mouth, and adjust the cavity to resonance. After effecting this, I remove the fork, and simply urge air through the glottis; I obtain this vowel sound *o*, and it is all that I can utter. Again, I take a third fork, adjust my mouth to it, and then urge air through the

larynx; the vowel sound *ah!* and no other is heard. In all these cases the vocal chords have been in the same constant condition. They have generated throughout the same fundamental tone, and the same overtones, and the changes of sound which you have heard are due solely to the fact that different tones in the different cases have been reinforced by the resonance of the mouth."*

70. Sensitive Flames.—Certain flames are found peculiarly sensitive to sonorous vibrations. This curious fact was made the subject of investigation by Tyndall, some years ago. His experiments led him to the discovery of some flames of remarkable delicacy.

In the course of some experiments subsequently on the same subject, the author was led to discover one of marvellous sensitiveness—he exhibited it at a meeting of the Royal Scottish Society of Arts, Edinburgh, a few years ago. The gas-flame, which was a long, narrow one, of 20 inches in height, issued from a glass burner, $\frac{1}{4}$ in. in diameter, tapering gradually to the $\frac{7}{100}$th of an inch, the aperture being U-shaped. Its behaviour was tested in a variety of ways. On using a penny whistle, and running over the different notes of the scale; it dipped more or less; while to a certain note sounded more loudly it shrank to the height of 4 or 5 inches, widening out at the same time. The *slightest* audible tap with a hammer on an iron plate affected it. It responded to each letter of the alphabet; but it was peculiarly sensitive to the letters C, H, P, Q, S, and T. On reciting a passage from Milton, it dipped almost to every word. The shaking of a small bunch of keys, 20 feet away, made it quiver. Clapping the hands, or even walking across the room, did the same. The ringing of a bell at the outside of the hall, with two shut doors intervening, and at the distance of a 100 feet, the bell being scarcely audible to those in the hall, made the flame quiver perceptibly.

It is difficult, if not impossible, to account satisfactorily for such wonderful results; but they serve to show with what marvellous readiness the air transmits vibration.

71. Optical Representation of Vibrations.—A striking method of giving optical expression to vibrations is that in-

* Tyndall on *Sound*, p. 199.

vented by Lissajous. It is represented in fig. 43. A narrow beam of light from an electric * lamp is allowed to fall upon a small mirror attached to a tuning-fork; the reflected beam is then received upon a larger mirror, held in the hands, and thrown by it upon a screen, placed at a convenient distance. When the fork is quiescent, there is seen upon the screen an image of the small orifice in the lamp through which the beam has issued. But when the fork is made to vibrate, that image moves rapidly up and down, and owing to the persistence of impressions on the eye (Art. 120), there is presented a band of light, which gradually shortens as the vibrations become smaller and smaller. Let now the large mirror be suddenly made to rotate, there is depicted on the screen a beautiful sinuous line, with the crests and hollows well defined at first, but which perceptibly diminish in depth as the vibrations of the fork decrease.

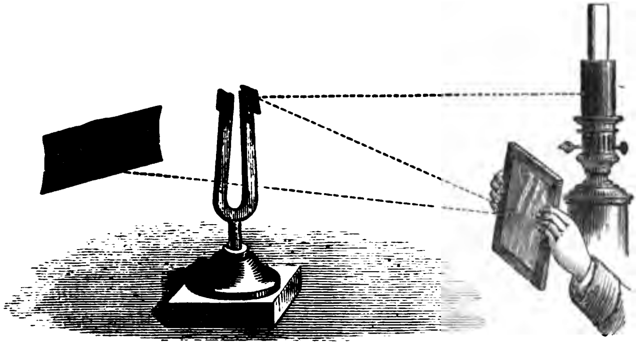


Fig. 43.—Graphic Representation of Vibrations.

Another method even more striking is by the use of the "Flame-manometer,"—a recent invention of König. It consists in making the sonorous waves, proceeding from any vibrating body, affect a gas-flame, which, by its pulsations, serve to indicate the nature of the sound. Fig. 44 shows the apparatus. The essential part consists of a capsule of wood or metal A, divided into two compartments by a piece of goldbeater's skin or sheet india-rubber. The compartment on the left is in com-

* An electric lamp gives a much better effect, though the figure represents an ordinary lamp, as being taken.

munication with a gas tube, and from it there also passes a small tube leading to the jet; whilst the right compartment is in connection with a funnel-shaped tube through which the sound passes. On the left of the diagram is a cubical box, with

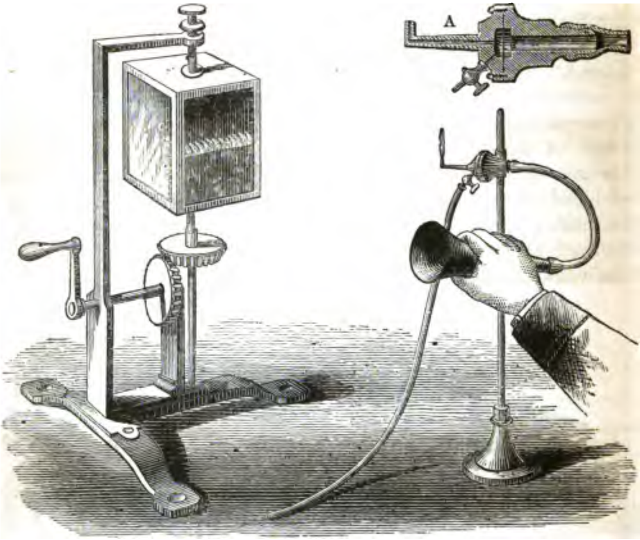


Fig. 44.—Manometric Apparatus.

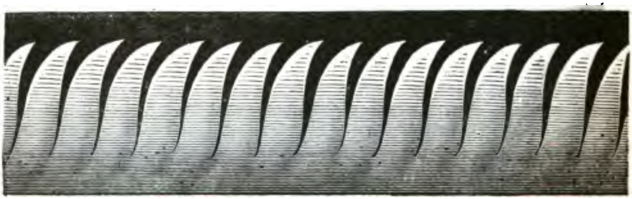


Fig. 45.

four of its sides provided with mirrors. This box is made to rotate by suitable mechanism. So long as no sound enters the funnel, the flame burns quite steadily, and when observed

in the rotating box, gives a continuous band of light. But when the sonorous waves of a body pass in, they throw the membrane into vibration, thereby affecting the pressure of the gas which goes towards the supply of the jet—the result is a rapid variation in the height of the flame, scarcely perceptible when looked at directly, but when viewed in the revolving box gives the appearance represented in fig. 45. A great variety of beautiful designs may be obtained by different sounds, or by their combination.

Fig. 46.

If the vowel *e* be sung into the mouth-piece on the note C, fig. 46 is obtained; and the vowel *o*, on the same note, fig. 47.

Fig. 47.

LIGHT.

CHAPTER I.

THEORIES OF LIGHT—PHOTOMETRY—VELOCITY.

72. Theories Concerning the Nature of Light:—

(1.) *Emission Theory.*—This was originally propounded by Newton—it sets forth that light consists of an imponderable substance, consisting of extremely minute particles of matter; that these corpuscles are emitted from luminous bodies with an enormous velocity, and that it is the impact of these minute corpuscles on the retina of the eye which produces the sensation of vision. This theory was subsequently defended by Laplace, Malus, and Biot; but it has now given way almost universally to that known as the undulatory theory.

(2.) *Undulatory Theory.*—This theory assumes at the outset that there exists everywhere in space an exceedingly rarefied but highly elastic substance, to which the name *ether* is given. This ether is believed not only to fill interstellar space, but to surround the molecules of all matter. The particles of luminous bodies are supposed to be in a state of extremely rapid vibration, and being surrounded by the all-pervading ether, there is generated in it a series of minute undulations or waves, proceeding with great velocity in concentric spheres. The sensation of vision is thus caused by the successive shock of these waves upon the retina. This theory was originally proposed by Huygens, and subsequently supported by Euler, Young, and Fresnel. It is adapted to explain, with perfect success, the varied phenomena connected with light; and, though the existence of ether is assumed—an existence of which we possess no

positive proof—it is much the more satisfactory of the two hypotheses.

73. Propagation of Sound and Light — Differences.—Light, like sound, therefore, is the result of *wave-motion.* But there are certain differences which it is important to notice. Sound requires some medium for its transmission, and cannot pass through a vacuum; light can as readily pass through a vacuum as through air. This is evident when we consider that the light from the sun and stars in reaching the earth has to pass through vacuous space. Again, whilst in sound the vibrations of the air take place in the direction in which the sonorous waves are propagated, in light the vibrations of the ether take place at right angles to the direction of propagation; in other words, in the former case the vibrations are *longitudinal*, and in the latter case *transversal.* Moreover, the waves of light are of extreme minuteness, and are transmitted with prodigious velocity.

74. Definitions.—A luminous *ray* is the tract or line which light takes in its propagation. According to the emission theory a ray of light is a train of luminous particles; according to the undulatory theory, *a ray is a line radiating from the centre of the luminous waves, and perpendicular to all the wave-fronts*—it has no material existence, but is only a direction.

An assemblage of rays is termed a *pencil* or *beam* of light; when the rays proceed in parallel directions, the pencil is said to be *parallel;* when they proceed in all directions, it is *divergent*, and when they converge towards a point, it is *convergent.* Parallel and convergent beams are met with in optical instruments; divergent beams are the most common, and are such as proceed from any luminous body.

75. Rectilinear Propagation of Light.—That light is propagated in straight lines is manifest from various facts. We cannot see round a corner. If we hold an opaque object in front of a candle, we fail to see the candle. If a small hole be made in the shutter of a darkened room, the track of a beam of light, as marked out by the floating particles of dust, is observed to be perfectly straight.

Towards sunset, when the sun is concealed by a cloud (fig. 48), straight beams of light are observed to radiate from

him in all directions, and to shed a glowing effect upon a surrounding landscape.

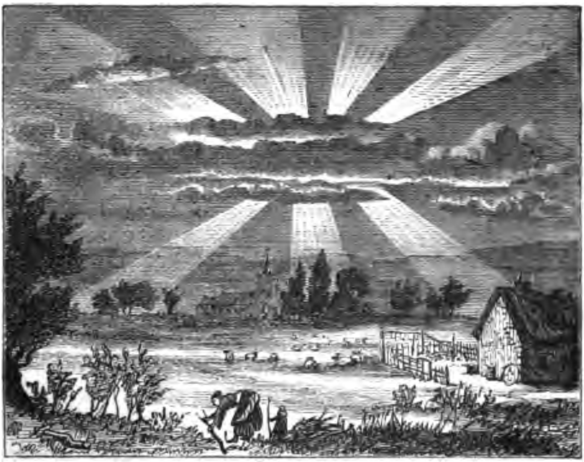


Fig. 48.—Light Proceeds in Straight Lines.

76. Inversion of an Object by Rays passing through a small Aperture.—This is a necessary consequence of the rectilinear propagation of light. Every point of a visible object emits rays in all directions. When an illuminated object is placed before a small aperture made in a dark chamber (fig. 49), the rays from the object which happen to fall on the aperture pass through it, and are received inside.

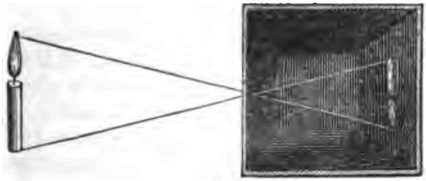


Fig. 49.—Crossing of Rays.

The rays *cross* each other at the aperture, and thus an *inverted* image is formed.

The shape of the image is precisely the same as that of the object, and is *independent* of the form of the aperture. This will appear manifest when it is considered that the object is made up of an infinite number of luminous points, each of which by itself would produce an image corresponding to the form of the aperture; but as these points are infinite in number, the different images overlap each other, and thus by their combination they give rise to one identical in shape to the object.

77. Shadow—Penumbra.—The shadow which an opaque body casts behind it when exposed to light is also a consequence of the same principle. In the case of a luminous point, it is easy to define or mark off the shadow. If, however, we have a luminous body, besides the true shadow, there is produced also a *partial* shadow or *penumbra*, as it is called.

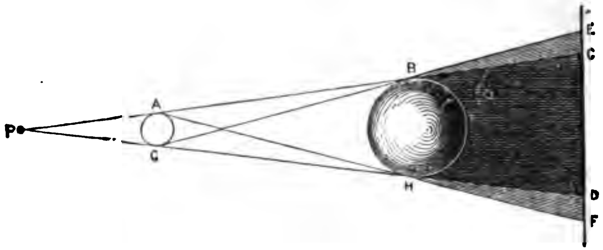


Fig. 50.

Thus, if P be a luminous point (fig. 50), and B an opaque spherical body, the shadow which it casts behind is marked off by the black part of the diagram, and shows itself on the screen, EF, as a dark circular disc, having a diameter CD. But if AG be the luminous body, the shadow BCDH is fringed with the lighter spaces BCE, HDF, which are exhibited on the screen as a shady circular ring surrounding the disc CD. This constitutes the *penumbra*.

In eclipses, both the umbra and penumbra are formed. An eclipse of the sun, as is well known, is caused by the moon coming between the sun and the earth.

The sun having sensible magnitude, the moon's shadow has not a sharp outline, but is surrounded by a penumbra, and being larger than the moon, the true shadow will be a

convergent cone. An observer, situated anywhere within this conical shadow, will see no portion of the sun, the eclipse will, in any such position, be total. An observer, situated outside the conical shadow of the moon, but within the divergent cone formed by joining points in the limb of the sun, with opposite points in the limb of the moon, will see a portion of the sun only; the eclipse will be to him partial.

Again, when the rays bounding the conical shadow of the moon intersect each other before reaching the earth, an observer, within the divergent cone so formed, sees an *annular* eclipse of the sun, that is, the moon's disc is seen on the sun, encircled with a ring of light.

It will be seen by reference to fig. 50, that the extent to which the umbra is fringed with the penumbra depends upon the distance of the screen from the opaque body; the nearer the screen the less the width of the penumbra. When the luminous body is the larger, the umbra being then a converging cone, the true shadow will entirely disappear if the screen be placed at the point of convergence. From this we can understand how the shadow of a small object, such as a hair, cast by the sun is obliterated, unless the surface on which it falls be very near. In general it is the angular magnitude of the sun which prevents the sharpness of solar shadows.

78. Intensity of Light.—The intensity of light diminishes with the distance from the luminous body according to the same law as that in regard to sound (Art. 24). It is well illustrated by the accompanying diagram (fig. 51).

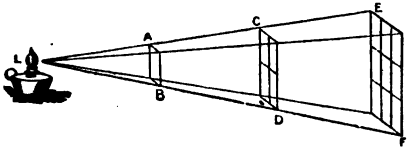


Fig. 51.—Inverse Square of the Distance.

Let a screen be placed at the distance of 1 foot from a lamp at L. Conceive a certain part of it, AB, illuminated. If the screen be removed to the distance of 2 feet, the same light which illuminated AB, in consequence of the divergence of

the rays, would now be cast upon a surface, CD, four times as great, therefore the intensity of the illumination there would be one-fourth of what it is at AB. At the distance of 3 feet, the same light would be cast upon a surface, EF, nine times as great, hence the intensity would be one-ninth of that at AB, and so on; the distances being, therefore, expressed by the numbers 1, 2, 3, 4, etc., the intensities will be expressed by the numbers 1, $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{16}$, etc.; or, generally, the intensity diminishes inversely as the square of the distance. We can see the truth of the law otherwise. The surfaces of spheres are proportional to the squares of their diameters. Suppose then three concentric spherical shells of diameters 1, 2, and 3 respectively, with a luminous body in the centre, the illuminated surfaces would be as 1, 4, 9; hence the intensities would be as 1, $\frac{1}{4}$, $\frac{1}{9}$.

From this law we can easily prove that if a surface be *equally* illuminated by two different sources of light, placed at given distances, the intensities of the two lights are *directly* proportional to the squares of these distances. Let I be the intensity of the one light, and I′ that of the other, at the unit of distance; d, and d' the respective distances from the illuminated surface.

The intensity upon the surface from the first $=\frac{I}{d^2}$; from the second $=\frac{I'}{d'^2}$, but the intensities at the given distances are equal—

$$\therefore \frac{I}{d^2}=\frac{I'}{d'^2} \text{ or } I:I'::d^2:d'^2$$

The intensity also varies as the cosine of the angle of incidence. This may be proved as follows:—

Let the beam, whose section is EF, fall on a surface, AB; call the intensity I; now let the surface be inclined, so that the same beam illuminates a larger portion of it, the intensity will be proportionally less, call it I′; then—

$$\frac{I'}{I}=\frac{AB}{AC}$$

Draw mn the normal to AC, put angle of incidence $= \alpha$.

$$\text{Then} \quad AB = AC \cos \alpha$$

$$\text{Therefore } \frac{I'}{I} = \frac{AC \cos \alpha}{AC} = \cos \alpha$$

$$\text{and } I' = I \cos \alpha,$$

or I' varies as $\cos \alpha$.

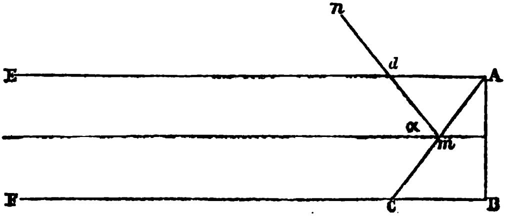


Fig. 52.

79. Photometry—Photometers.—*Photometry* is the art of comparing the intensities of different sources of light. How this can be accomplished will be readily understood from what has been stated above. Several instruments have been invented for this express object; these are termed *photometers* (literally "light-measurers"). We shall only describe two of them.

(1.) **Rumford's Photometer.**—This method is sometimes known as the "*shadow test.*" It consists in making the two lights, A and B (fig. 53), cast shadows of a rod C upon a

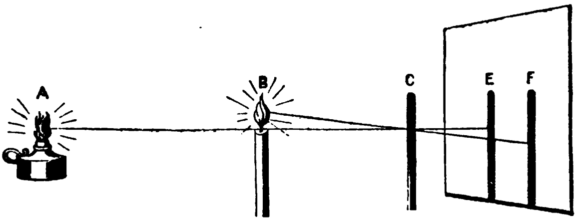


Fig. 53.—Rumford's Photometer.

screen, and adjusting the lights till the shadows at E and F are illuminated to an equal degree. Then, since the shadow E is illuminated by the light B, and the shadow F by the light A, and these shadows are equally bright, it follows that

the lights A and B cast the same quantities of light on the screen at their respective distances. If B be 2 feet from the screen, and A, 5 feet, the relative intensities will be as 4 to 25, or which is the same thing, A gives $6\frac{1}{4}$ times as much light as B.

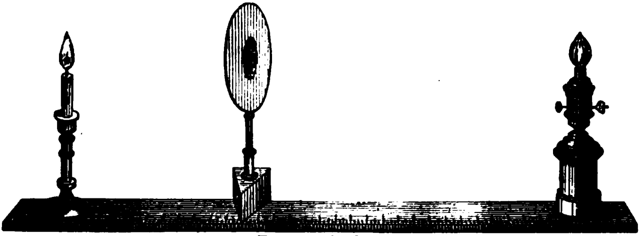


Fig. 54.—Bunsen's Photometer.

(2.) **Bunsen's Photometer.**—This is represented in fig. 54. It consists of a flat graduated scale, on which a mounted disc is made to slide. The disc is a paper screen, having a greased spot in the centre. The lights to be compared are placed on opposite sides of this disc, and are adjusted so that the spot may appear of the same brightness as the other parts of the paper, from whichever side it is viewed. The distances being measured, the intensities are ascertained as before. The principle of the instrument is as follows:—When the disc is held up in front of a light, and viewed from the other side, the greased spot, owing to a greater transmission of light, appears brighter than the rest of the paper; if viewed from the same side as that from which the light comes, it appears darker. If, therefore, two lights be used, and the disc be adjusted so that the spot will appear neither brighter nor darker than the rest of the paper when viewed from either side, it indicates that the same quantity of light is transmitted through the greased part of the paper by the two lights at their respective distances.

This instrument is extensively used for testing the illuminating power of coal gas. The standards usually adopted are 5 cubic feet of gas and 120 grains of sperm candle consumed per hour, and when the quantities burned during any experiment do not correspond with these, the results are rectified by

calculation. The illuminating power of gas in this country varies from 12 sperm candles up to about 30.

The intensity of sunlight at the surface of the earth has been estimated as equivalent to 5563 moderate-sized wax candles at the distance of one foot.

80. Velocity of Light—Aberration.—This is a very interesting problem, and fraught with considerable difficulty, inasmuch as the rate of transmission is very rapid for any known terrestrial distance.

The velocity of light was first determined by Rœmer, a Danish astronomer, in 1675. He deduced it from certain observations on the first satellite of Jupiter. He observed that an eclipse of the satellite took place about 16 minutes sooner, when the earth was in conjunction with Jupiter, than when in opposition—this difference he properly accounted for by supposing that such was the interval of time which the last glimpse of light sent off by the satellite, as it entered Jupiter's shadow, took to traverse the earth's orbit. From this, he calculated the velocity to be about 192,000* miles per second.

In 1824, Bradley deduced the velocity from what he termed the *aberration* of light. He noticed that a star, whose position in the heavens he could previously calculate, could not be seen by a telescope, if pointed directly to the spot indicated, unless a certain slope were given to it. If a star were in the zenith, for example, it could not be seen by the telescope held vertically. This result is owing to the combined effect of the earth's motion in her orbit, and the passage of light from the star. Suppose an individual to stand in the midst of a shower of rain on a quiet day, he would receive the drops directly on his head; but let him run forward, his own motion along with that of the rain would make the drops come upon his face; and if he carried a sloping open tube in his hand, some rain-drops, though falling vertically, might pass right through the tube. This may serve to illustrate the phenomenon of aberration.

The angle through which the telescope required to be

* The calculation proceeded upon the old estimate of the sun's distance. Taking the newer estimate of 91 millions of miles, this number must be reduced.

moved from its vertical position was found to be 20·45″. This is called the *constant of aberration*. Knowing this angle, and the earth's speed in her orbit, he calculated the velocity of light to be 190,860* miles per second.

The most recent investigation is that of Cornu. Two stations were fixed upon, whose distance was accurately known—a beam of light was transmitted from the one to the other, and thence returned by reflexion to the first, the interval of time required for the double journey being the matter for determination. The method was an improvement on that followed out by Fizeau in 1849. The principle of the method is thus described by Cornu:—"A beam of light is sent across the teeth of a moving wheel, which beam is reflected from the opposite station. The luminous point, which results from the return of the rays, appears fixed, notwithstanding the interruptions of the beam, owing to the persistence of the impressions upon the retina. The experiment consists in ascertaining the velocity of the toothed wheel which extinguishes this *luminous echo*. Extinction occurs when, in the time necessary for the light to traverse double the distance of the stations, the wheel has substituted a tooth for the *interval* between two teeth which permitted the passage of the light at starting. . . . The mechanism of the toothed wheel permits a velocity of the latter exceeding 1600 revolutions per second; the chronograph and electric recorder ensure the measurement of time to the thousandth of a second." By this method, Cornu, in taking the mean of a number of experiments, computes the velocity at 186,616 miles per second.

This prodigious velocity will be more readily conceived of when we state, that whilst light takes about 7 minutes to travel from the sun to the earth, a cannon ball, retaining its initial velocity of 1600 feet per second, would perform the same journey in 17 years, and an express train going at the rate of 40 miles an hour in 265 years.

Notwithstanding this enormous speed, the nearest stars are so far off that their light takes between three and four years to reach us; and it has been presumed that the more distant stars in the universe are so remote, that the light

* Also founded on the old estimate of the sun's distance.

from them may take hundreds or even thousands of years to reach our globe.

81. Invisibility of Light—Tenebroscope.—A beam of light entering by a shutter in a darkened room is rendered visible by its illuminating the particles of dust in its track. Were there no dust particles, the beam would be invisible. A striking proof of this is afforded by placing the end of a poker made white-hot at some point in the course of the beam, the dust particles are burnt up, and the end of the poker is shrouded in darkness. If several white-hot bodies be so placed, the beam is seen broken up into several parts.

The *tenebroscope*, invented by the Abbé Moigno, is an instrument adapted to illustrate the same fact. It consists of a tube, blackened inside, and closed at one end; the tube is perforated with two apertures directly opposite to each other, through which a beam of light is made to pass. Notwithstanding the passage of the beam, on looking in, all is dark, but by means of a simple mechanism a small ivory ball is raised into the course of the rays, and immediately becomes visible.

CHAPTER II.

REFLEXION OF LIGHT.

82. Two Kinds of Reflexion.—A ray of light is said to be *reflected*, when it is sent back into the medium through which it came.

Two kinds of reflexion are distinguished: (1) *irregular* or *scattered*, and (2) *regular*. If a beam of sunlight, for example, be admitted through an aperture in the shutter of a darkened room, and allowed to fall upon a sheet of white paper, the beam is irregularly reflected or scattered; whereas, if allowed to fall upon a plane mirror, it is reflected regularly, that is, the reflected beam takes a definite course.

It is owing to irregular reflexion from the surfaces of objects that they become visible to us. Did they not possess the power of thus scattering the light which falls upon them, they would be invisible. In consequence of irregular reflexion on the part of the atmosphere, we have the sun's light pleasingly diffused all around us, and gladdening so unsparingly the entire animal and vegetable creation.

83. Reflexion from Plane Mirrors—Laws.—If light fall upon a polished surface, such as a plane mirror, it is *regularly* reflected, that is, it is sent off the reflector in a definite direction. Thus, let A B be a plane mirror (fig. 55). If the ray of light fall perpendicularly upon it, as in the direction F D, it is reflected directly back again. But if it come in the direction C D, then it is reflected in the direction D E, the angle C D F being equal to the angle F D E. The angle C D F is called the *angle of incidence*, and the angle F D E the *angle of reflection*. Moveover, the *incident* ray C D and the *reflected* one D E are in the same plane, which is perpendicular to the reflecting surface. The laws of regular reflexion, therefore, may be expressed thus: (1) *the angle of reflexion is equal to the angle of incidence*, and (2) *the incident*

and reflected rays are in the same plane; and that plane is perpendicular to the reflecting surface.

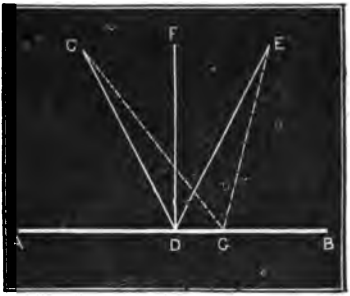


Fig. 55.—Regular Reflexion of Light.

It is easily proved, geometrically, that the course C D E is the *shortest* possible from the points C, E, to the mirror. It is shorter, for example, than the course C G E.

The mirrors of the ancients consisted of polished metal. Ordinary looking-glasses date from the 12th century; as now constructed, they are plates of glass coated at the back with an amalgam of quicksilver and tin.

84. Experimental Proof of the Laws of Reflexion.—A simple proof of the laws of reflexion is afforded by the apparatus represented in fig. 56. To the centre of a graduated semicircle is attached a small mirror, M; A and B are two tubes blackened inside, adjusted to move along the arc, and directed towards the central point. The arc is graduated from the middle point towards either extremity. Suppose the tube A to be placed at the division marked 30, and to receive the light from a candle, then it would be found that the tube B must be adjusted to the division 30 on the other side of the zero point, in order that the candle be seen.

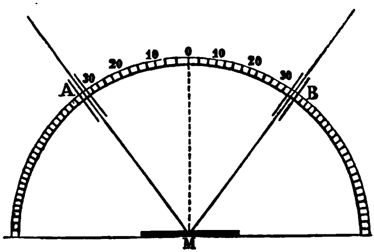


Fig. 56.—Experimental Proof.

85. Formation of an Image by a Plane Mirror.—When an object is placed before a plane mirror, its image is seen *as far behind the mirror* as the object itself is before it. This is a consequence of the foregoing laws.

Firstly, let us take the case of a point A (fig. 57); the rays from it, after reflexion by the mirror, enter the eye of a spectator at E in a state of divergence — the eye receives these rays as if they came from the point A′ behind the mirror. By geometry, it is easily proved that the distance $A'0 = A0$; hence the truth of the proposition.

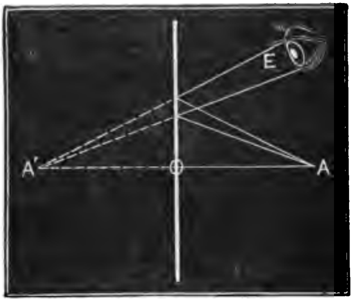


Fig. 57.—IMAGE OF A POINT BY A PLANE MIRROR.

Secondly, let A B be an object (fig. 58), the rays from A, after reflexion by the mirror, enter the eye as if they came from a real object at A′; similarly, the rays from B enter the eye as if they came from B′; and intermediate points in A B are seen at intermediate points in A′ B′. Thus, an image of A B is seen at A′ B′. The image thus formed is called a *virtual* image.

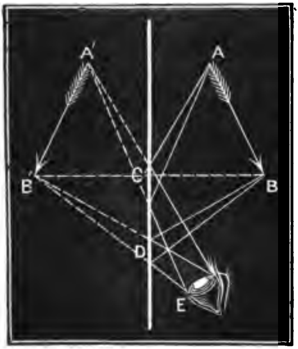


Fig. 58.—IMAGE OF AN OBJECT.

86. Lateral Inversion.—The image formed by a plane mirror has the same size and shape as the object, but differs in regard to *position*. If, for example, a person stand before a looking-glass, his right eye is the left in the image, and his left eye the right in the image. This effect is known as *lateral inversion*. Hence, writing written backwards is adjusted by being held before a mirror, and can be read as if it were written in the ordinary way. Take a card and write any word, such as "light," in the ordinary way and backwards; when held before a mirror, the reflexion will give the appearances as in fig. 59. Or, more simply, write down the word, and take the impression on a piece of white blotting-paper—then hold the card and blotting-paper before the mirror.

Types set up for printing can be read off easily in this way. So, also, the blocks prepared for wood-cut illustrations can be examined before being cut out.

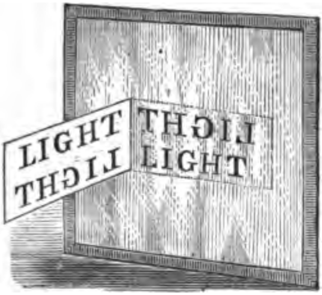


Fig. 59.—LATERAL INVERSION.

87. Experiments with a Common Looking-Glass.—Some interesting experiments may be performed with a common looking-glass. If a candle be held directly between the eye and the mirror, one image only of the candle is seen. Now, if the candle be moved gradually towards the side of the mirror, a series of images more and more detached from each other are observed, the second of the series being the brightest and best defined. The experiment is more successful in a darkened room, and with a mirror having a thick glass.

To understand these results, let M be the mirror and A a small object (fig. 60) placed before it. The rays on falling upon the mirror are partly reflected at the anterior surface, and partly enter the glass. In virtue of the rays that are so reflected, an image is seen at *a*. The rays which enter the glass suffer *repeated* reflexion from the two surfaces, but upon each reflexion at the anterior surface a portion of the rays pass out, and entering the eye, form an image. The *second* image *b*, which is the brightest, results from the reflexion at the silvered surface of the glass. Its distance from the first image is double the thickness of the glass (see Art. 88). The successive images *c*, *d*, etc., become fainter and fainter as the reflexion continues, owing to the diminution in the quantity of light which

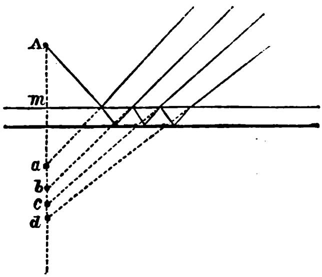


Fig. 60.

escapes after the different reflexions. When the object is directly between the eye and the mirror, the series of images overlap each other, and but *one* image is seen.

If the candle be held close to the mirror, whilst the eye is adjusted in a corresponding position, the first image appears as bright as the second—affording a proof that there is *an increase* in the amount of reflexion with the *obliquity* of the angle of incidence.

If a mirror be set at an angle of 45°, a pencil held vertically before it, appears in a horizontal position, and when held horizontally, appears vertical—both easy deductions from the laws of reflexion.

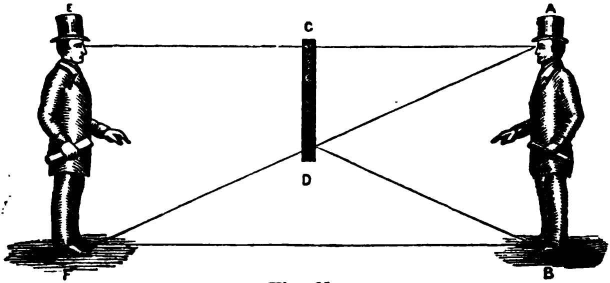


Fig. 61.

An individual may see his whole person in a mirror *half* his height.

This will appear from fig. 61. The triangles A C D, A E F, are similar, ∴ A C : C D :: A E : E F; alternately A C : A E :: C D : E F; but A C = $\frac{1}{2}$ A E; hence, C D = $\frac{1}{2}$ E F = $\frac{1}{2}$ A B.

88. Relative Velocity of Mirror and Image.—(1.) *If a mirror be moved parallel to itself, either from or towards an object, the image moves twice as*

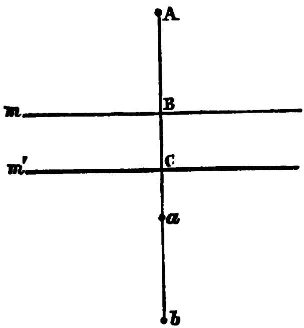


Fig. 62.—Mirror Moved Parallel.

fast. Let m, m', be two positions of the mirror (fig. 62), A the object, a, b, the respective images.

$$\text{Then } A\,C = Cb, \text{ and } A\,B = Ba;$$
$$\therefore\ A\,C - A\,B = Cb - Ba;$$
$$\text{that is, } B\,C = Ca + a\,b - (B\,C + Ca) = Ca + a\,b - B\,C - Ca = ab - B\,C;$$
$$\therefore\ 2\,B\,C = a\,b.$$

(2.) *If a mirror be made to rotate, the angle through which the image moves is twice the angle through which the mirror moves.* Let A B be the mirror (fig. 63), and C D a ray of light normal at D. The reflected ray returns along the same line. Let A B now revolve through Z A D A′ to position A′ B′. Let D E be the normal to A′ B′; make E D F = E D C.

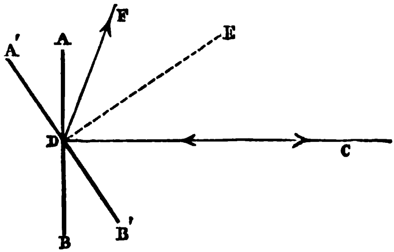


Fig. 63.—Rotating Mirror.

Then DF is the direction of the reflected ray and CDF is the angle moved through by the ray. Now—

$$\angle\ A'\,D\,E = 90 = \angle\ A\,D\,C;$$
$$A'\,D\,E - A\,D\,E = A\,D\,C - A\,D\,E;$$
$$\text{that is, } A'\,D\,A = C\,D\,E;$$
$$\text{but, } C\,D\,F = 2\,C\,D\,E,$$
$$\therefore\ C\,D\,F = 2\,A'\,D\,A,$$

or the angular velocity of the reflected ray is double that of the rotating mirror.

89. Illusory Effects from Glass Plates.—The reflexion which takes place from a plate of polished glass may be applied to produce illusory effects. Thus, if a candle be placed before such a plate, and a carafe of water behind it; whilst the carafe is seen directly through the transparent glass, an image of the candle is seen by reflexion, and the

appearance is presented of the candle burning inside the carafe (fig. 64).

Fig. 64.—ILLUSORY EFFECT.

In the exhibition known as "Pepper's Ghost," a large sheet of plate glass is set up at the back part of the stage, slightly inclined towards the spectators, and so adjusted as scarcely to be seen. The so-called "ghosts" are the images of persons below the stage, hid from view, and illuminated by the electric or lime light. The real actors who are in front of the glass plate are thus seen to hold converse with imaginary beings.

90. Repeated Reflexion—The Polemoscope.—As has been stated in Art. 87, light is capable of *repeated* reflexion—that is, being reflected over and over again.

An instrument sometimes called the "optical wonder" is constructed on this principle. A section of it is represented in fig. 65. Two tubes, A and B, mounted on hollow pillars,

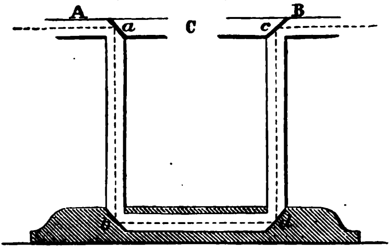


Fig. 65.—OPTICAL WONDER.

are supported on a wooden base which has a longitudinal perforation. *a, b, c, d,* are four small mirrors, set each at an angle of 45°. The course of the rays is sufficiently indi-

cated in the diagram. Whatever opaque object, therefore, be placed between the tubes at C, there can be no interruption to the vision.

The "polemoscope" acts on the same principle. It is represented in fig. 66. Two mirrors are used in the instrument, each set at an angle of 45°. The upper mirror being directed towards a distant object, the rays of light from the object are reflected by it and sent down upon the lower mirror, when they are again reflected, and where an image of the object is seen.

Fig. 66.—THE POLEMOSCOPE.

The officers behind a fortification or parapet can, with this instrument, watch the movements of the enemy without exposing themselves to danger, and can thus give orders to their men how to direct their fire to the best advantage.

91. Multiplication of Images—The Kaleidoscope.—When two plane mirrors are set at right angles to each other, an object placed between them yields three images. Thus, let B C, C D (fig. 67), be the mirrors, and A the object. An image of A is formed in the mirror B C at A′, a second in the mirror C D at A″, whilst a third image is formed by a double reflexion of the rays at A‴. The three images and the object are in the angles of a rectangle. If A be at equal distances from the mirrors, they are in the angles of a square. The number of images increases as the angle between the mirrors diminishes. If the angle be 60°, there are 5 images; 45°, 7; 30°, 11. In general, to find the number we have only to divide 360° by the angle between the mirrors, and diminish the quotient (if a whole number) by unity. Hence if the angle be 0°, that is, if the mirrors be parallel, the number of images is infinite, but practically the images become in the end so feeble as to cease to be visible. That

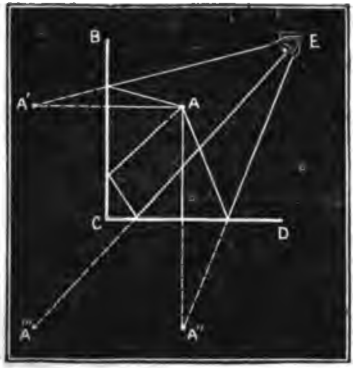


Fig. 67.—Multiplication of Images.

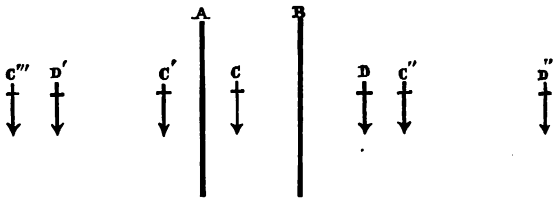


Fig. 68.—Infinity of Images.

there is *theoretically* an infinite number of images, may be seen from the following reasoning: Let A and B be the two mirrors, and C an object placed between them. An image

of C is formed at C′ by the mirror A, as far behind as the object is before; but C′ serves as an object for the mirror B, an image of it, therefore, is formed at C″, as far behind B as C′ is before it. Similarly, an image of C″ is formed at C‴ by the mirror A. Again, an image of C is formed at D by the mirror B. This serves as an object for the mirror A, and an image of it is formed at D′, and so on *ad infinitum*.

An arrangement of this kind is sometimes called the "endless gallery," and is used in ball-rooms, picture galleries, jewellers' shops, etc., in order to add to their appearance and produce a dazzling effect.

The *kaleidoscope* (invented by Brewster) depends for its effect upon the multiplication and symmetrical arrangement of images. It consists of a tube of metal or cardboard, in which are placed two strips of smoked glass, or better still, silvered glass set at an angle; at the end are the small objects, such as pieces of coloured glass, beads, straws, etc., confined between two glass discs. Looking through the narrow aperture at the other end, and turning round the instrument, an infinite variety of arrangement is effected in the small objects, and therefore also an infinite number of beautiful forms is presented to the eye. Fig. 69 shows the arrangement of the images obtained in the case of one object, when the angle between the reflectors is 60°.

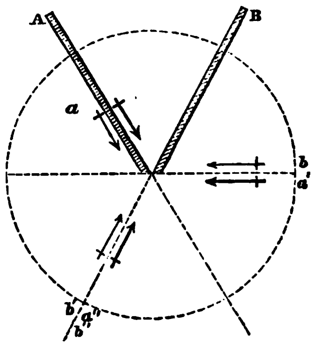


Fig. 69.—Principle of the Kaleidoscope.

An improved form of the instrument known as the "New Jewel Kaleidoscope" has recently been introduced, in which the object glass is movable; some of the objects being small glass tubes filled with fluid of different colours. The movements of the fluid, as the object glass is turned round, produce very beautiful effects. A curious calculation has been made in reference to the number of changes which could be obtained by the new instrument. Supposing 10 changes

per minute to be effected, the *entire* variety of designs would not be exhausted till after the lapse of 460,000 millions of years!

92. Reflexion from Curved Mirrors—Concave Spherical Mirrors.—The most common forms of curved reflectors are the *concave* spherical and the *convex* spherical.

The first of these is the more important to notice. Let A B be the mirror (fig. 70), O the centre of the spherical shell, of which the mirror forms a portion, C D a line drawn through O and the middle point of the mirror. This line is termed the *principal* axis. Rays passing from the point O are reflected directly back. If the rays come from an infinite distance, or from the sun, they may be considered as coming in parallel directions, and after reflexion by the mirror, they are concentrated in the point F, midway between O and D.

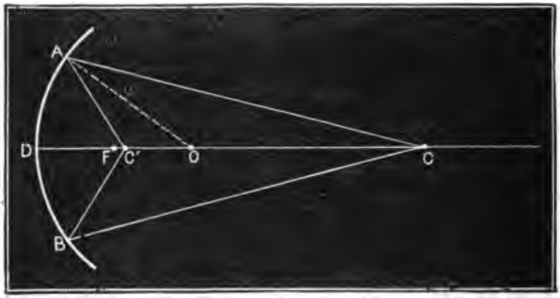


Fig. 70.—Concave Mirror.

This point is called the *principal* focus. But if they come from a point C, the divergent beam is concentrated at some point C′, such that the angle C A O is equal to the angle C′ A O, and an image of C is thus formed at C′. Let now the point C approach the mirror, the focus C′ will move towards O. Passing O, the focus of the rays moves along O C, until the point comes to C, when C′ now becomes the position of the image. The two points C, C′, are thus interchangeable—they are called *conjugate* points or foci. When the luminous point coincides with F, the rays after reflexion pass in parallel directions. If the point still approach the mirror, the rays become divergent, and form no *real* focus, but if produced

backwards, as in fig. 71, they meet in some point C′, that is, an eye placed at E will receive the rays as if they came from C′. In such a case C′ is called a *virtual* focus.

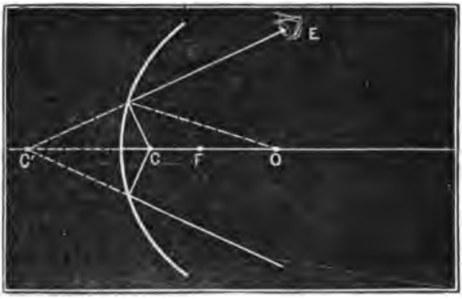


Fig. 71.—VIRTUAL FOCUS.

If the luminous point be *not* placed on the principal axis, the position of its image is determined as in fig. 72. Draw C D through the point O—this is termed a *secondary* axis. The rays are brought to a focus upon this axis at some point C′, between the principal focus and the centre of curvature, as before.

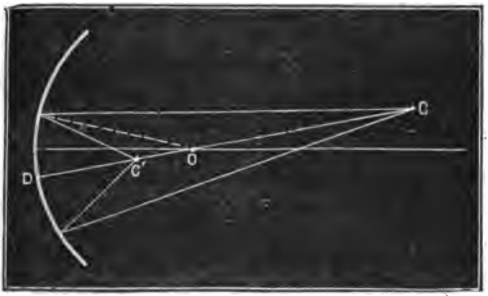


Fig. 72.—FOCUS ON SECONDARY AXIS.

The formation of the image of an object by this kind of mirror will now be easily understood. Let A B be the object (fig. 73); the rays from A will be brought to a focus at A′, and the rays from B at B′. Thus there will be formed between F and O an image A′ B′, smaller than the object, and

inverted. Similarly, if A′ B′ be the object, A B will be its image. Both these images are formed in the air in front of the mirror, and are, therefore, *real* images.

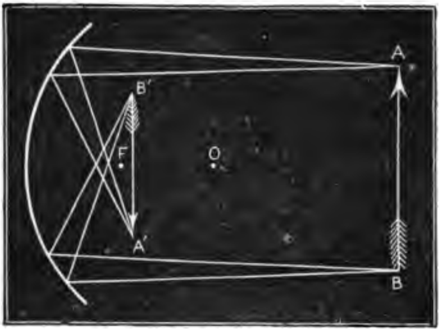


Fig. 73.—Real Image in a Concave Mirror.

If the object be placed between the principal focus and the mirror (fig. 74), then the rays from the object A B enter the eye at E, as if they came from an object behind the mirror at A′ B′. In this case the image has the *same* position as the object, and is magnified. It is a *virtual* image.

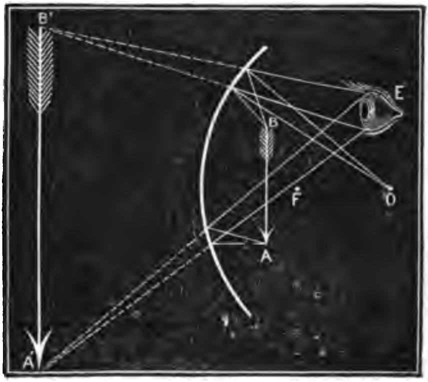


Fig. 74.—Virtual Image.

It is evident that the *size* of the image bears the same

relation to that of the object as the distance of the former from the mirror to the distance of the latter.

93. Convex Spherical Mirror.—If parallel rays fall upon a convex mirror, these rays, after reflexion, diverge as if they came from a point F on the other side of the mirror (fig. 75). This point, as before, is the principal focus (virtual), and is situated about half-way between the centre of curvature O and the mirror.

If the luminous origin be at C, the rays after reflexion become more divergent, and the virtual focus c', is *between* the principal focus and the mirror.

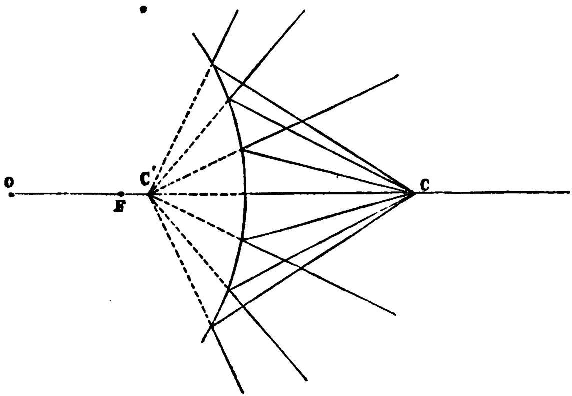


Fig. 75.—VIRTUAL FOCUS IN A CONVEX MIRROR.

Fig. 76 shows how the image of an object is formed by such a mirror. The nearer the object, the more divergent the rays after reflexion, the less, therefore, the image; but it is always *erect*.

General formulæ to find the position of the image of a point object formed by a spherical mirror.—

Let $DC = p$, $DC' = p'$, and $DO = R$ (fig 70),

$$\frac{OC'}{OC} = \frac{AC'}{AC} \text{ (Euc. VI, 3.)}$$

$$\therefore OC' \times AC = OC \times AC'.$$

If the arc A D does not exceed 4 or 5 degrees, the lines C A, C′ A, are approximately equal to C D, C′ D, that is, to p and p'.

$$\text{Now, } OC' = OD - C'D = R - p'$$
$$\text{and } OC = CD - OD = p - R$$

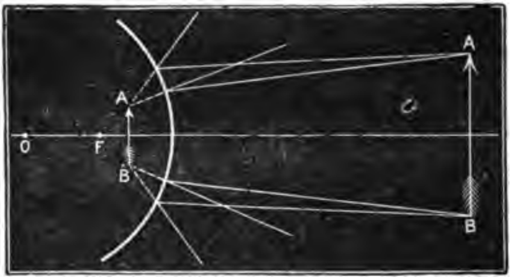


Fig. 76.—IMAGE IN A CONVEX MIRROR.

Substituting these values in the former equation—

$$(R - p')\,p = (p - R)\,p'$$
$$Rp - pp' = pp' - Rp'$$
$$Rp + Rp' = 2\,pp', \text{ and dividing by } pp'R$$
$$\frac{1}{p'} + \frac{1}{p} = \frac{2}{R} \text{ or } p' = \frac{R}{2 - \frac{R}{p}}$$

If f = principal focal length,

$$\text{Then, } \frac{1}{p'} + \frac{1}{p} = \frac{1}{f}$$

(1.) If the object be placed at an infinite distance, then $p = \infty$, and $\frac{R}{p} = 0$, hence $p' = \frac{R}{2}$, that is *the principal focus is mid-way between the centre of curvature and the mirror.*

(2.) In the case of a *convex* spherical mirror, both p' and f must be taken negative. Writing, therefore, $-p'$ and $-f$ in the above formula, we have

$$-\frac{1}{p'} + \frac{1}{p} = -\frac{1}{f},$$

$$\text{Hence } \frac{1}{p'} - \frac{1}{p} = \frac{1}{f}.$$

(3.) Taking the formula for the concave spherical mirror, we can deduce the case of a *plane* mirror.

In a plane mirror the radius must be considered as infinite; hence,

$$f=\infty, \text{ and } \frac{1}{f}=0.$$

We have, therefore,

$$\frac{1}{p'}+\frac{1}{p}=0, \text{ or } p'=-p.$$

that is, the image of C is as far *behind* (the negative implies this) the mirror as C is before it.

94. Spherical Aberration—Caustics.—All the rays from a luminous point which fall upon a concave spherical reflector, are not concentrated into a *single* point, as we have been supposing. When the *aperture* of the mirror, as it is called, is small—in other words, when the portion of the mirror round the principal axis is small—not exceeding 8° or so, the convergence of the rays to one point is sensibly true. The rays which fall upon the marginal parts of the mirror are not thus concentrated—these, by their intersection with each other, give rise to a series of images forming a luminous surface, which is called a *caustic*. The inability of a concave mirror to collect the rays falling upon it into one point is called *spherical aberration*.

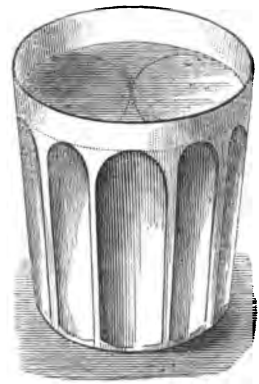


Fig. 77.—CAUSTIC CURVE.

It may be so far obviated by interposing an opaque diaphragm in such a way as to restrict the rays to a small portion of the mirror round the principal axis. The caustic curve may be well seen by placing a common glass tumbler nearly filled with milk beside a candle; the rays are thrown down by the interior face of the glass, and exhibit the curve upon the lacteal surface (fig. 77).

It may be more strikingly seen by exposing a bright curved metallic band, placed on a piece of paper, to the sun's

rays. In this case, the rays being parallel, the curve formed is a determinate one. It is known as the *epicycloid;* it is the curve traced out by a point in the circumference of one circle as it rolls upon another. The same curve is obtained should the rays diverge from points in the spherical shell, of which the reflector is a portion. In other cases it is not a determined curve.

95. Parabolic Mirror.—Let a parabola (fig. 78), whose focus is F, revolve round its principal axis A B, it will trace out a paraboloidal shell. A mirror of this shape is generally called a *parabolic* mirror.

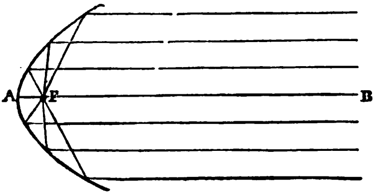


Fig. 78.—Parabolic Mirror.

If such a mirror be exposed to parallel rays, they are all concentrated in the focus of the generating parabola—there is no aberration. Conversely, if F be the luminous origin, the rays after reflexion are sent out in parallel directions. Reflectors of this kind are sometimes used in lighthouses to send out to sea, as far as possible, a parallel pencil of light. The source of light, however, being of sensible magnitude, *all* the rays are not strictly parallel, hence the beam does not reach so far as it otherwise would. They are used also in carriage lamps and railway trains.

CHAPTER III.

REFRACTION OF LIGHT.

96. Two Kinds of Refraction.—*Definition*—A ray of light, in passing from one medium into another, is said to be *refracted*, when it deviates from the direction in which it was proceeding before entering the new medium. The deviation itself is called *refraction*.

There are two kinds of refraction, called respectively *single* and *double*. Single refraction takes place in liquids, glass, etc., and in certain crystallised bodies, as rock-salt and alum. Double refraction, on the other hand, takes place in other crystallised bodies, as Iceland spar, selenite, etc. The former kind of refraction is the one to be treated of in the present chapter.

97. Laws of Single Refraction.—Take the case of a ray of light passing from air into water (fig. 79). If the ray enter the water in the direction A O, perpendicular to the surface, it suffers no refraction, but goes straight through; if it enter in any other direction, such as A′O, instead of pursuing the straight course O C, it is bent from it, and takes a new direction O D. Whilst the angle A′O A is the angle of incidence, the angle DOB is termed the *angle of refraction*.

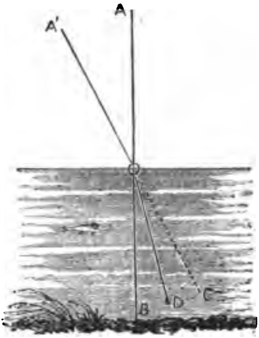


Fig. 79.—REFRACTION.

The behaviour of the ray is therefore this: when it passes from air into water it is refracted *towards* the perpendicular; conversely, if it passes from water into air, it is refracted *from* the perpendicular. Such is generally the behaviour of a ray of light passing (1) from

a rare medium into a denser, and (2) from a dense medium into a rarer. A curious exception, however, is found in the case of spirit of turpentine and water. The former fluid has a *less* density than water—a ray of light passing from it into water is refracted *from* the perpendicular, and, conversely, from water into the spirit *towards* the perpendicular.

But to express more definitely the principle of refraction, let a circle be described with any radius O A (fig. 80). Draw A′ F, D G, perpendicular to A B, then it is found, whatever be the magnitude of the angle A′ O A, that the relation between these lines is always the same for the same media. Assuming the radius of the circle to be *unity*, and calling the angles of incidence and refraction i, i', respectively, then A′ F, D G are the sines

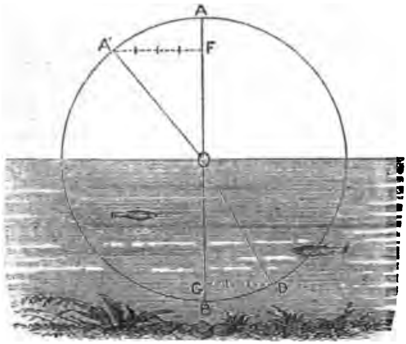


Fig. 80.—Law of Refraction.

of these angles. Hence we have $\frac{\sin i}{\sin i'}$ = a constant quantity = m (suppose). This ratio is called the *index of refraction.* For air and water its magnitude is $\frac{4}{3}$, or 1·333. Moreover, the incident and refracted rays are in the same plane.

The laws of single refraction may therefore be stated thus:

(1.) *The sine of the angle of incidence bears to the sine of the angle of refraction a constant ratio for the same two media.*

(2.) *The incident and refracted rays are in the same plane; and that plane is perpendicular to the common surface of the two media.*

98. Experimental Proof of the Laws of Refraction.—Take a cell B C D F, with glass sides, having one opaque end B C, as in fig. 81. Let a lamp be placed at A, the shadow of B C will reach to some point E. Measure off the lines B C, C E. If, now, water be poured into the vessel so as to fill it, the shadow will retreat to the point H, the ray of light

A B being refracted in the direction B H. Again measure off the line C H. From these data, B H and B E can easily be calculated by geometry. Then, $\frac{CE}{EB}$ = sin i, and $\frac{CH}{HB}$ = sin i'; hence $\frac{\sin i}{\sin i'}$ becomes known. Now, it is found that whatever be the magnitude of the angle of incidence, this relation, as determined by the above method, is always the same.

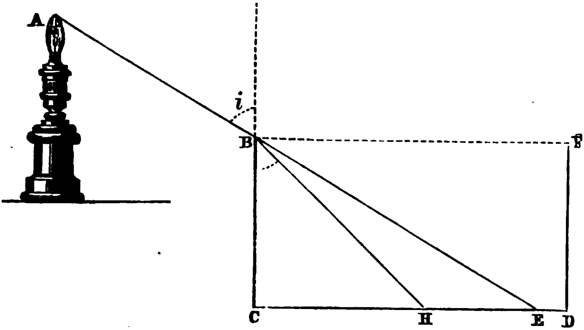


Fig. 81.—EXPERIMENTAL PROOF.

99. Effects of Refraction.—The refraction of light explains a number of familiar phenomena. A pool of water appears shallower than it really is. To understand this, let A (fig. 82)

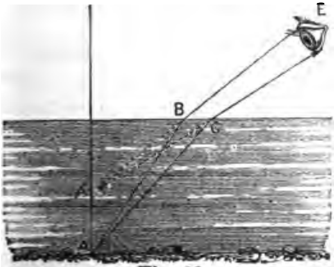


Fig. 82.

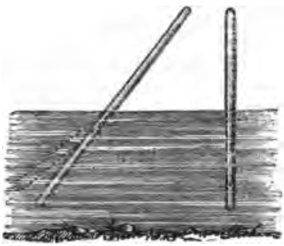


Fig. 83.

be a point in the bottom, the rays A B, A C, in emerging from the water, are refracted in the directions B E, C E, and enter

the eye there as if they came from the point A′ near the perpendicular, that is, the point A will be seen at A′. The same is true of every other point, hence the whole bottom of the pool appears lifted up. From this it is manifest that the more divergent the rays B E, C E are, in other words, the greater the obliquity of the vision, the shallower will the pool appear. The apparent shallowness is *least* when the eyes look directly down into the pool, the depth in this case being diminished a fourth—that is, if the pool is really 12 feet deep, it will appear to be only 9 feet.

A stick placed vertically in water (fig. 83) appears shortened, and placed obliquely appears bent, the immersed portion being raised by refraction.

An object under water appears not only less deep, but also of a different shape (fig. 84). Thus the object A B will appear to have the position and shape A′ B′.

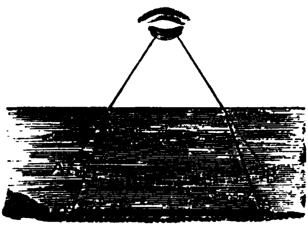


Fig. 84.

A boat floating in clear water seems to have a flatter bottom than it really has, so also a deep-bodied fish seems contracted.

A striking effect of refraction is exhibited by the following experiment:—Place a coin in a bowl, and retire until you just lost sight of the coin by the interposition of the edge. Now desire a companion to fill the bowl with water, the coin again comes into view.

In consequence of refraction by the atmosphere, we never see the heavenly bodies in their true places, except those which are directly over our heads. The amount of displacement near the horizon is estimated at about half a degree, but it diminishes rapidly towards the zenith. When we see the lower edge or limb of the sun or moon apparently just touching the horizon, the whole disc is actually below it. Hence refraction tends to prolong the stay of the sun and moon above the horizon—it hastens their rising, and delays their setting.

Even after the sun has disappeared below the horizon, the refraction of his rays continues for some time, which, com-

bined with reflexion, produces the phenomenon of *twilight*, by which we pass, with so pleasing a gradation, from the effulgence and activity of day to the darkness and stillness of night.

It is a common observation to notice on a warm sultry day a *quivering* appearance of objects at a distance. This is due to irregular refraction on the part of the heated air which rises from the surface of the earth, the rays of light from the distant objects undergoing thereby a constant shifting in their direction. The following experiment is strikingly illustrative of this point:—A beam of light from an electric lamp at L (fig. 85) is made to pass through the flame of a Bunsen burner B, and is received upon a screen at S. The strong heat of the burner gives rise to the uplifting of heated air-currents, which, acting on the intense light of the electric beam, reveals the appearance of smoke rising upon the screen. A similar effect is presented when the beam is made to pass through hydrogen, or other gas escaping from a vessel.

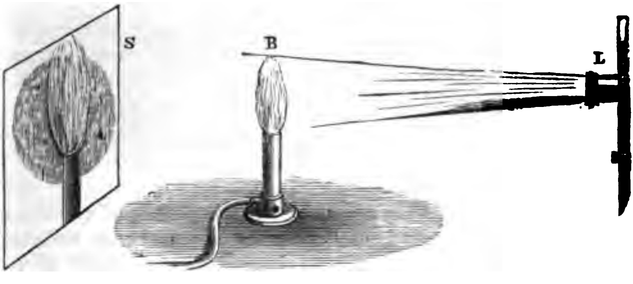


Fig. 85.—Quivering caused by Refraction.

100. Refraction is always accompanied by Reflexion.—Wherever there is refraction, there is also reflexion. We cannot have the one without the other. Should the one disappear, so will the other. The higher the refractive power of a substance, the greater the amount of reflexion; hence the striking brilliancy of the diamond.

If a solid be immersed in a fluid having the same refractive index as itself, it would cease to be visible.

It will not be difficult, therefore, to understand the appearance presented on the margin of a river or lake. Thus, in fig. 86, the rays from the objects on the opposite bank partly enter the water, suffering refraction, and are partly reflected from the surface towards the observer. In virtue of this partial reflexion, inverted images of the objects are seen, and they are *feeble*, because of the loss of that portion of the light which passes into the water.

101. Transparency—Opacity of Transparent Mixtures.—There is no body perfectly transparent, that is, none which allows perfect freedom in the transmission of light. Water, for instance, is transparent at ordinary depths, but even then a number of rays are quenched. At the depth of a few hundred feet it loses all its transparency. The dimness of the sun and moon in the horizon is owing to some of the light being quenched in its passage through the atmosphere.

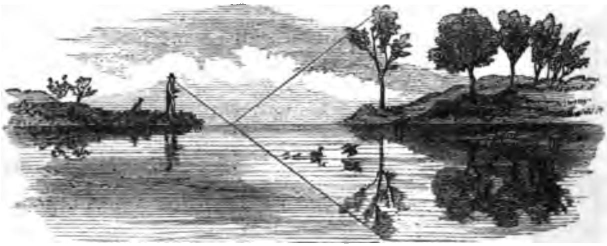


Fig. 86.—Images seen in Water.

"In the passage from one medium to another of a different refractive index, light is always reflected; and this reflexion may be so often repeated as to render the mixture of two transparent substances practically impervious to light. It is the frequency of the reflexions at the limiting surfaces of air and water that renders *foam* opaque. The blackest clouds owe their gloom to this repeated reflexion, which diminishes their *transmitted* light, hence also their whiteness by *reflected* light. To a similar cause is due the whiteness and imperviousness of common salt, and of transparent bodies generally when crushed to powder. The individual particles transmit light freely; but the reflexions at their surfaces are so numerous that the light is wasted in echoes before it can

reach to any depth in the powder. The whiteness and opacity of writing paper are due mainly to the same cause. It is a web of transparent fibres, not in optical contact, which intercept the light by repeatedly reflexing it. But if the interstices of the fibres be filled by a body of the same refractive index as the fibres themselves, the reflexion of the limiting surfaces is destroyed, and the paper is rendered transparent. This is the philosophy of the tracing-paper used by engineers, It is saturated with some kind of oil, the lines of maps and drawings being easily copied *through it* afterwards. Water augments the transparency of paper, as it darkens a white towel; but its refractive index is too low to confer on either any high degree of transparency."*

102. Total Reflexion—The Limiting Angle.—In order that a ray of light may *pass* from a dense medium into a rarer, the angle of incidence must not exceed a certain limit. For water and air this angle is about 48½°, and is called the *limiting* or *critical* angle of refraction. Thus, let AB be the the incident ray (fig. 87), then if the angle ABC = 48½°, the refracted ray will emerge in the direction BE, or nearly parallel to the surface of the water. If the angle ABC be greater than 48½°, then the ray is *reflected*—the reflexion obeying the ordinary law. It follows from this, that all the incident light embraced in the angular space DBE, is condensed by refraction into the space ABC, or that the *whole* light which passes into the water is condensed into an angular space of 97°.

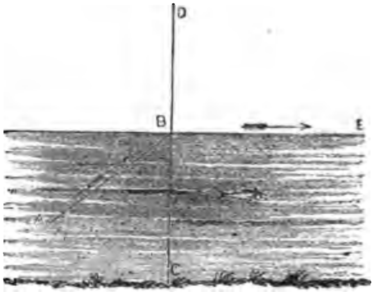


Fig. 87.—The Critical Angle.

We can imagine, therefore, what kind of appearance is presented to a diver, in still shallow water, when he looks upwards: all external objects will be seen, as it were, through a circular aperture overhead of 97° in diameter, whilst be-

* Tyndall's *Notes on Light*, p. 19.

yond this circle he will see, by the effect of total reflexion, the various objects at the bottom as distinctly as if he looked directly at them. A man standing on the shore, as well as the shore itself, would appear to be lifted up.

Total reflexion may be well illustrated by placing a coin in a tumbler of water, and sloping the tumbler till the light acquires the proper incidence. On looking upwards a distinct image of the coin is seen towards the surface of the water. In an aquarium, if the eye be directed to the surface of the water, the various objects in it may be rendered visible in a like manner.

103. The Mirage.—The unusual elevation of islands, coasts, ships, etc., above the surface of the sea, in certain states of the atmosphere, has been long known. The image of a distant ship, for example, has been seen suspended in the air, sometimes erect, at other times inverted. These strange phenomena are observed from time to time on our own coasts, but are witnessed with greater frequency, and more strikingly, in the Arctic regions. Captain Scoresby, the famous Arctic navigator, is said to have recognised his father's ship by its inverted image in the air, though it had not yet actually appeared above the horizon.

These effects are due to refraction, and occur when the atmosphere is warmer than the surface of the sea. The inferior layers of air, because of their contact with the surface of the sea, are denser than those above. The density of the successive layers therefore diminishing upwards, the rays of light from a ship AB (fig. 88), in passing through them are refracted *from* the perpendicular, and at length becoming incident at angles greater than the *limiting* angle (Art. 102), are totally reflected at such points as C and D; in returning through the strata they are now gradually bent *towards* the perpendicular, and enter the eye of an observer at E, as if they came from an object at A′B′. Thus an image of the distant ship is seen suspended in the air. The *inverted* image, sometimes seen, is accounted for by supposing that the rays, before they reach the eye, *cross* each other.

The term *mirage* was first applied to this class of phenomena, by one of the members of Napoleon's expedition into Lower Egypt, in 1798. During the march of the French

army through the sandy deserts, it was frequently observed that the land seemed to be terminated at a certain distance by a general inundation. The distant villages appeared to be so many islands planted in the midst of the apparent flood, with inverted images of them beneath. These appear-

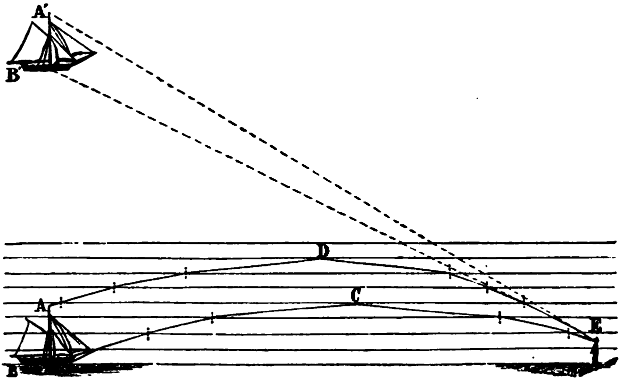


Fig. 88.—The Mirage.

ances are explained in a similar way, with this difference, that the strata of air in immediate contact with the warm sandy plain have less density than those above; the rays therefore, after *total reflexion*, enter the eye, and produce an *inverted* image, analogous to what occurs on the surface of a lake (fig. 86).

104. Transmission of Light through Glass Plates.—When a ray of light passes obliquely through a plate of glass with parallel surfaces, it emerges in a direction *parallel* to the incident ray. This is evident when we consider that the ray in entering the plate must be as

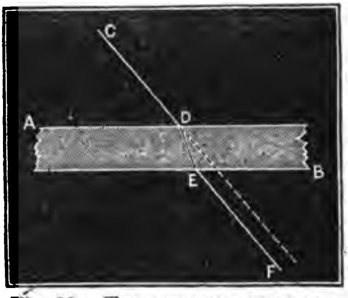


Fig. 89.—Transmission through a Glass Plate.

much refracted towards the perpendicular as it is refracted from it on passing out. Thus let AB be the plate (fig. 89), the ray CD upon entering the glass is refracted in the direction DE; on emergence it is again refracted, and pursues the course EF parallel to CD. A certain amount of deviation thus ensues, and that deviation is the greater the thicker the glass.

Such deviation necessarily occurs in looking obliquely through the panes of glass in a window; but the thickness of the glass being small, the displacement of objects viewed through them is insignificant.

If a ray of light be made to pass through several such media (fig. 90), the emergent ray is also parallel to the incident ray. The amount of deviation is of course augmented.

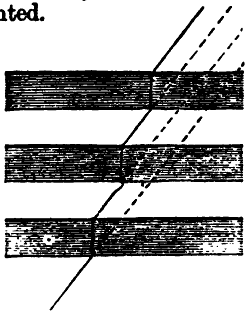


Fig. 90.—Transmission through several Plates.

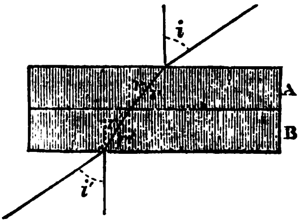


Fig. 91.—Transmission through Plates of Different Material.

Should the media be of different material, the emergent ray is still parallel to the incident ray. This circumstance enables us easily to determine the index of refraction between two media, if the index of refraction between air and each of them be known. Thus, let A and B be two media (fig. 91), m and n their respective indices, and i, r, r' the several angles in the figure of incidence and refraction.

Then $$\frac{\sin i}{\sin r}=m, \text{ and } \frac{\sin i}{\sin r'}=n$$

$$\therefore \sin i = m \sin r; \ \sin i = n \sin r'$$

Hence $$m \sin r = n \sin r'$$

And $$\frac{\sin r}{\sin r'}=\frac{n}{m}, \text{ which gives it.}$$

Example.—Given the index of refraction from air into water $=\frac{4}{3}$, and from air and glass $=\frac{3}{2}$; determine the index of refraction from water into glass,

$$\text{Index required} = \frac{\frac{3}{2}}{\frac{4}{3}} = \frac{9}{8} = 1{\cdot}125.$$

105. Prisms—Course of a Ray through a Prism.—A *prism*

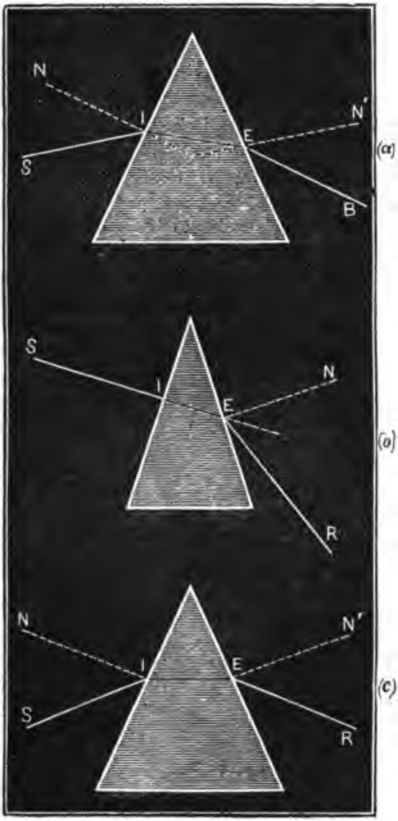


Fig. 92.—Treatment of Homogeneous Light by a Prism.

in optics is a wedge-shaped transparent substance, constructed generally of glass. The angle enclosed by the two oblique faces is called the *refracting* angle of the prism.

The treatment of a ray of *homogeneous* light by a prism is this: Let SI be the ray (a), and IN the perpendicular upon the face at the point of incidence; the ray is refracted *towards* the perpendicular, and follows the course IE inside the prism. On emergence it is again refracted, but now *from* the perpendicular upon the other face, EN′, in the direction EB. Thus the ray is bent twice in the same direction, that is, *towards the base of the prism.* If the incident ray (b) be perpendicular to the face of the prism, there is only one refraction, and that takes place at the point of emergence, in the direction ER.

If, again, the incident ray (c) so fall as that the refracted ray IE becomes parallel to the base, then the emergent ray ER is such that the angle REN′ = the angle SIN. In this case the deviation of the incident ray from its original course is the *least possible.*

This can be proved experimentally, and the amount of deviation can be measured for a prism of any refracting angle.

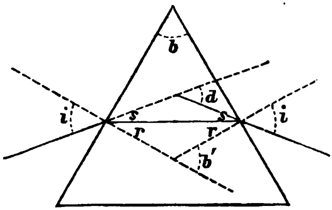


Fig. 93.—Determination of Index of Refraction.

106. Determination of Indices of Refraction.—If the *minimum* deviation of a prism and its refracting angle be known, it is easy to determine the index of refraction of the substance of which it is composed. Draw the lines as in fig. 93, and name the angles by the different letters.

Then $b' = 2r$, but $b' = b$

$\therefore\ b = 2r$ or $r = \frac{1}{2}b$.

Again d (angle of deviation)

$= 2s = 2(i - r) = 2i - 2r = 2i - b$

$\therefore\ i = \frac{1}{2}(b + d)$.

$$\text{Hence index of refraction} = \frac{\sin i}{\sin r} = \frac{\sin \frac{1}{2}(b+d)}{\sin \frac{1}{2}b}.$$

In order to determine the indices of different fluids a

hollow prism is prepared, with sides of plate glass, nicely polished, and having parallel surfaces; as the direction of the rays is unaltered in passing through the glass (Art. 104), what deflection takes place must result from the enclosed fluid.

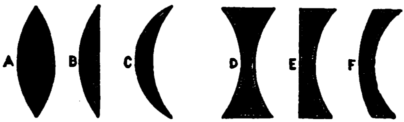
We append the indices of different substances, as determined by this method:—

Air into		*Air into*	
Ice,	1·310	Crown glass,	1·530
Ether,	1·358	Flint glass,	1·635
Alcohol,	1·365	Diamond,	2·487
Canada balsam,	1·530	Chromate of lead,	2·927

The last of these substances has the greatest refractive power of any yet discovered.

107. Lenses—Converging and Diverging.—A lens is a portion of a refracting substance, such as glass, having its bounding surfaces either both curved, or the one plane and the other curved. Lenses are of two classes, *converging* and *diverging*, and are named from the form of their external surfaces. Each class comprises three kinds.

Thus (fig. 94), A is called a *double convex* lens; B, a *plano-convex;* C, a *concavo-convex* (or *meniscus*), the *convex* surface having the greater curvature. D is called a *double concave* lens; E, a *plano-concave,* and F, a *convexo-concave,* the *concave* surface having the greater curvature.



Converging. Fig. 94. *Diverging.*

The effect of a *converging* lens as A, and of a *diverging* lens as B, on a beam of light, will be understood from figs. 95, 96.

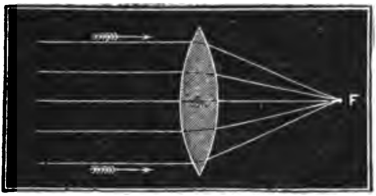


Fig. 95.—Effect of Converging Lens on Parallel Rays.

Let the beam consist of parallel rays; the lens (A, fig. 95) brings the rays to a focus at the point F. This point is called the *principal* focus, that is, it is the focus of parallel rays. It is a *real* focus.

In an ordinary lens of crown glass, where the curvature of both surfaces is the same, the principal focus *nearly* coincides with the centre of curvature. The distance of F from the nearest surface of the lens is called the *principal* focal distance.

Again, the lens B (fig. 96) causes the rays to diverge, as if they came from a point F′, on the same side of the lens on which the light falls. This point is therefore the *principal* focus. It is evidently a *virtual* focus.

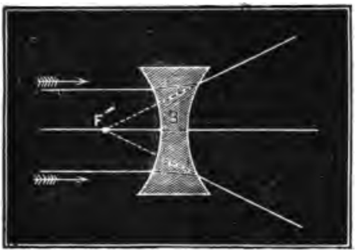


Fig. 96.—Effect of Diverging Lens on Parallel Rays.

It may be noticed that a converging lens is thicker and a diverging lens thinner at the centre than at the exterior borders. They may be distinguished very easily in this way.

108. Formation of an Image by a Double Convex Lens.—Let us first take the case of a luminous point placed before a double convex lens. Let A be the luminous point (fig. 97); draw A A′ through the centre of the lens, perpendicular to its two convex surfaces—this is termed the *principal* axis. The rays from A are brought to a focus at a point A′ beyond the principal focus F, and a *real* image of A is formed there.

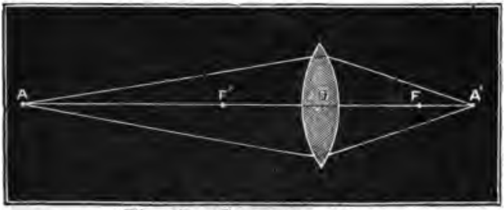


Fig. 97.—Conjugate Foci.

These two points, as before, are convertible; they are conjugate foci. If A now be moved towards the lens, A′ will retire from it, until A coincides with the principal focus F′ (O F being equal to O F), when the rays, as in fig. 95, will emerge from the lens in parallel directions.

If A be placed between F′ and the lens (fig. 98), the rays, after passing through the lens, are divergent, proceeding as if they came from a point A′. The point A′ is therefore a *virtual* focus.

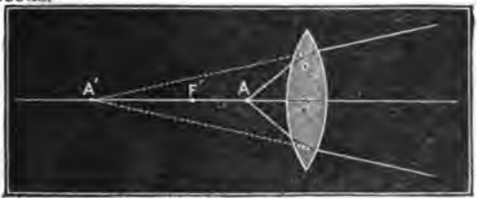


Fig. 98.—VIRTUAL FOCUS.

Let now an object AB be placed before the lens beyond the principal focus (fig. 99). Draw AOA′ and BOB′ through the centre of the lens. The rays from A are brought to a focus at A′, those from B at B′, and the rays from intermediate points in AB at intermediate points in A′B′. Thus a real inverted image of AB will be formed at A′B′. This image may be seen by an eye placed beyond A′B′, or it may be projected on a screen, whose distance from the lens is equal to that of A′B′. The size of the image bears the same proportion to the size of the object, as the distance OA′ does to OA.

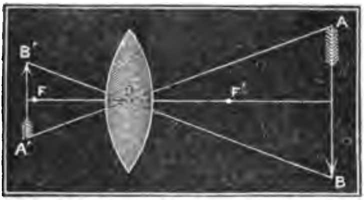


Fig. 99.—FORMATION OF AN IMAGE BY A CONVEX LENS.

If the object be placed *between* the lens and the principal focus (fig. 100), a magnified and erect image will be formed. Then, of course, the

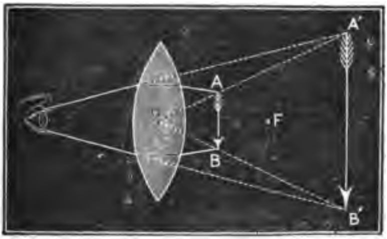


Fig. 100.—SIMPLE MICROSCOPE, OR MAGNIFYING GLASS.

image is virtual. Such an arrangement constitutes the *simple* microscope.

109. Formation of an Image by a Double Concave Lens.—We have seen that a double convex lens may give either a real or a virtual image, according to the distance of the object. A double concave lens gives only a virtual image at all distances. Let AB be the object (fig. 101), FC the principal axis, F the principal focus. The rays from AB, after traversing the lens, are divergent, and enter the eye as if they came from a real object at A′B′, that is, there will be an image of AB seen at A′B′, between the lens and the principal focus. That image is erect and smaller than the object.

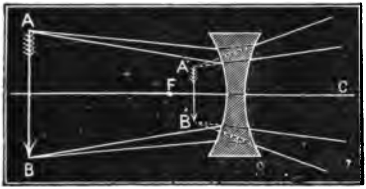


Fig. 101.—FORMATION OF AN IMAGE BY A CONCAVE LENS.

It will be observed that whilst with a convex lens either a real or a virtual image may be obtained, with a concave lens only a *virtual* image is possible, the former is analogous in its action, therefore, to a concave mirror, and the latter to a convex mirror.

110. Spherical Aberration.—We have been proceeding upon the supposition that *all* the light passing through a lens is brought to the same focus. This, in reality, is not the case. The rays which fall upon the exterior borders of the lens are *not* concentrated into the same point, but are found to intersect each other at different points, forming a luminous surface, which is called a *caustic*, by refraction (Art. 92). This inability on the part of a lens to bring all the rays to a single focus, is called *spherical aberration.*

This aberration interferes with the sharpness or distinctness of an image, but may be partly obviated by interposing an opaque diaphragm provided with a central aperture. This allows the rays *only* which fall upon the central part of the lens to pass through. Recourse is had to this device in photography.

111. Explanation of Reflexion and Refraction by the

Undulatory Theory.—The undulatory theory of light asserts, as we have seen, that *a series of undulations or waves* are generated in the all-pervading ether by the luminous body, which are propagated in concentric spheres. A ray of light, according to this theory, has no material existence; it is a line drawn from the luminous centre perpendicular to the wave-fronts, and thus indicates the direction in which the waves are propagated.

(1.) **Reflexion.**—We know that when a stone is dropped into a pool of still water, a wave is generated, which gradually enlarges as it proceeds outwards from the centre of disturbance. Suppose that it encounters some reflecting surface, such as a smooth wall, its outward course is checked; but a little observation will reveal to us that its motion is not arrested; the wave now returns so far upon itself, and goes on still enlarging as if it came from another centre of disturbance, similarly situated to the original one, on the other side of the obstacle. If a *series* of waves are propagated, they all behave in a similar way.

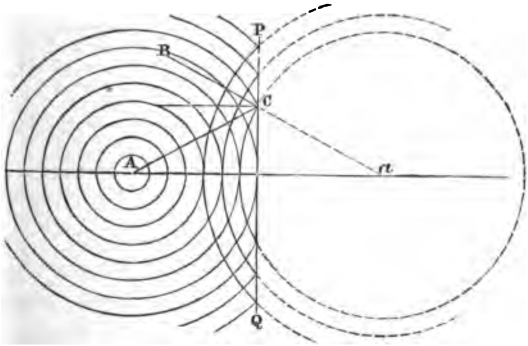


Fig. 102.—Reflexion of Waves.

The same thing is believed to take place with ether-waves. The various incident waves proceeding from the luminous centre A (fig. 102), on meeting the reflector P Q, proceed as if they emanated from a new centre *a*, at an equal distance on the other side of the reflector. Drawing any radius A C, which thus represents a *ray* of light, and completing the con-

struction indicated in the figure, we see that it is reflected in the direction B C, such that the angle of reflexion is equal to the angle of incidence. The waves of sound are reflected in a similar manner.

(2.) **Refraction.**—To account for refraction, it is assumed—and the assumption is quite borne out by results—that, in a refracting medium, *the density of the ether is increased in a greater proportion than the elasticity.* The consequence is, as in the case of sound, that the velocity of light in such a medium is *diminished;* in other words, the refracting medium exercises a *retarding* influence upon the passage of the etherial waves.

This being premised, let us take the case of light entering a plate of glass with parallel surfaces. Suppose the lines in fig. 103 to represent *small* portions of a series of waves emanating from a luminous centre—if that centre is distant, they are sensibly straight lines, and parallel to each other. If the waves impinge perpendicularly, their course is unaltered; but in passing through the glass, their velocity is diminished.

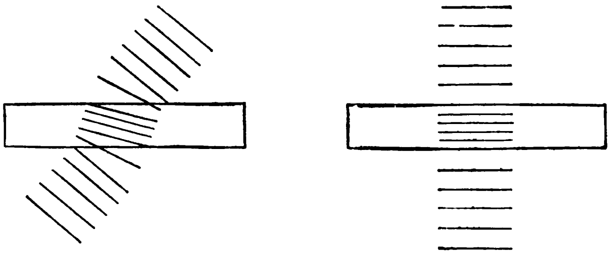


Fig. 103.—Treatment of Waves by Refracting Surfaces.

This is indicated in the figure by the smaller distance of the lines from each other. If they impinge obliquely, the ends of the waves which first enter the glass are retarded, whilst the other portions preserve their original motion until they in succession reach the glass, when a similar retardation ensues. This causes the waves to swing round, and thus they take a different course in the glass from what they had previously—in a word, they are *refracted.* But now, on reaching the

lower surface, the ends of the waves which were first retarded are the first to escape, the other portions being held back until they in turn make their exit. The consequence is that they are swung round a second time, in virtue of which, when they have fairly emerged, they regain their former course.

The action of lenses will thus be easily understood—the different portions of the ethereal waves are successively retarded as they enter the glass.

We are now in a position to give a more precise signification to the term "index of refraction." In fact, it simply expresses the *relative velocities of light* in the two media in question. Thus, for example, when it is stated that the index from air into water is $\frac{4}{3}$, it implies that the velocity of light in air is to that in water as 4 : 3, in other words, the velocity in air is $1\frac{1}{3}$ times the velocity in water. Again, the index from air into glass being $\frac{3}{2}$, this indicates that the velocity of light in air is $1\frac{1}{2}$ times what it is in glass.

CHAPTER IV.

THE EYE—FAR SIGHT AND SHORT SIGHT—STEREOSCOPE.

112. Structure of the Eye.—The different parts of this wonderful organ are exhibited in fig. 104.

The opaque coating *a*, known popularly as the "white of the eye," consists of tough fibrous tissue, and is called the *sclerotica*. The front part, *c*, is an extension of this coat, with the important difference, however, of being transparent, and is called the *cornea*. In the posterior chamber, in immediate contact with the sclerotica is the *choroides b*, a delicate membrane of winding blood-vessels, covered over with a black velvety pigment,* obviously to prevent internal reflexion. Inside this again is the *retina g*, a very fine network of nerves; upon this as a curtain or screen the images of objects are focussed, and being an extension of the optic nerve *h*, which communicates with the brain, the impressions give rise to the sensation of vision. Behind the cornea is the *crystalline lens e*, having the form of a double convex lens of unequal curvature, highly elastic, and consisting of concentric layers of tissue which increase in consistency, and therefore in refractive power, towards the centre. It is held in its place by the *ciliary* membrane, which is acted upon by a series of muscles called the *ciliary muscles f*. *d* is the *iris*, a curtain or diaphragm in connection with the ciliary membrane, having a central opening called the *pupil m*. The iris is differently coloured in individuals,

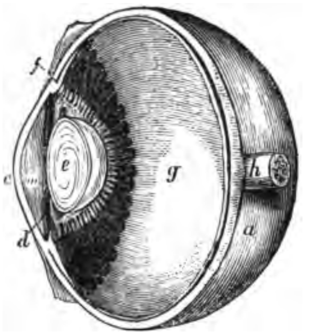


Fig. 104.—EYE-BALL PARTLY IN SECTION.

* It has been found, lately, by physiologists, that a coloured or dark pigment is also necessary for proper hearing and smell. When it is absent, as in perfectly white animals, these senses are defective.

giving rise, therefore, to difference of colour in eyes. The iris performs the important function of regulating the quantity of light which passes into the interior chamber of the eye, by its enlarging or contracting the diameter of the pupil. When the eye is exposed to a great glare of light, the edges of the iris, which are in close contact with the lens, approach, and thus contract the pupil; when there is little light passing in, the pupil is expanded. The changes which the iris undergoes, however, require time; hence the impression produced when a person passes from a highly illuminated room into the open air at night; he imagines it darker than it really is—the fact is, he emerges with his pupil in a very contracted state, and it is not till after some time has elapsed that his pupil dilates sufficiently to allow him to form a more correct judgment. The anterior and posterior chambers of the eye are filled with fluid which are called respectively the *aqueous humour*, from its resemblance to water, and the *vitreous humour*, resembling more a delicate jelly than a regular fluid.

113. Distinct Vision.—In order that we may see any external object *distinctly*, an image of that object must be thrown upon the retina; in other words, the rays of light from the object must be brought to a focus there. This is effected chiefly by the intervention of the cornea; but the other parts of the eye, the aqueous humour, the crystalline lens, and the vitreous humour, are all concerned in the refraction of the rays.

That an image of an external object is actually depicted upon the retina, has been shown by experimenting with the eye of a recently slaughtered bullock. What holds good of a bullock's eye is believed to be true of the human eye. The image also is *inverted*, the reason of which is obvious. For ordinary eyes, there is a certain distance at which an object must be placed, in order that it may be seen with the greatest possible distinctness. The *distance of distinct vision*, as it is termed, in the case of small objects, such as common type, varies from 10 to 12 inches.

The field of vision is very considerable. In looking at any object, objects in its vicinity are also seen, though not with such precision. The range for each eye embraces, it is

calculated, an angle of 160° laterally, and for both eyes an angle somewhat exceeding two right angles. The vertical range is about 120°.

114. Punctum Cœcum—Fovea Centralis.—It is a remarkable fact, and one which can scarcely be credited, that, though the optic nerve is the medium of communication with the brain, when the image of an object falls upon the *base* of that nerve (h, fig. 104), there is no impression produced—it is quite insensible to the action of light. The following interesting experiment may be made in corroboration:—Put three spots of ink on a sheet of paper, about three inches apart. Shut one eye, and look steadily with the other at any of the spots. If now the head be slowly moved towards either side, up or down, a position will be obtained where one of the three spots entirely disappears. By a little care any one of the spots may be made to vanish. This is owing to the image falling upon the surface in question. From this circumstance the surface has been called the *punctum cœcum*, or "blind spot."

"This blind spot is so large that it might prevent our seeing eleven moons if placed side by side, or a man's face at a distance of only 6 or 7 feet. Mariotte, who discovered the phenomenon, amused Charles II. and his courtiers, by showing them how they might see each other with their heads cut off." *

Perhaps a simpler method of proving the existence of the "blind spot" is afforded by the accompanying illustration (fig. 105). Shut the right eye and look steadily at the asterisk —if the book be placed at a distance of 10½ inches, the whole 5 black spots disappear. By varying the distance of the book from the face, one or more spots become visible.

Fig. 105.—Proof of "Blind Spot.

This fact seems to corroborate the opinion now held generally by physiologists, that the retina is not absolutely the

* Helmholtz's *Popular Scientific Lectures*, p. 222.

seat of vision, but rather that it is excited indirectly by certain structures in connection with it, resembling *rods* and *cones*. These rods and cones are found wanting at the base of the optic nerve, and hence its insensibility.

Every part of the retina is not equally sensitive to the action of light. There is a small portion where the organization seems to be more perfect, and is therefore more delicate than any other. This part is called the *yellow spot*, so named from its colour. In the middle of it is a slight depression termed the *fovea centralis*, upon which, if the image of an object fall, it is seen with the greatest possible distinctness. When we *look* at an object, the eye is so directed as to secure the formation of the image upon this small area. Fig. 106 is a representation of the posterior half of the eye-ball which has been cut across. The two spots are here shown; the one to the right is the base of the optic nerve, towards which the blood-vessels of the retina are seen to converge.

Fig. 106.—POSTERIOR HALF OF EYE-BALL.

115. Why Objects are Seen Erect.—Since the image of any external object depicted upon the retina is *inverted*, a natural question arises, how do we correct this inversion? Some have supposed that we actually do see everything inverted, but that, from habit and experience, we learn to assign to every object its true position. According to this opinion, infants see objects upside down; and it is only by comparing the erroneous information acquired by vision, with the more accurate information acquired by touch, that they learn to see objects as they really are. Others again account for it by supposing that we really judge of the position of an object from *the direction in which the rays of light proceeding from it enter our eyes.*

116. Single Vision.—As there is an image of the object in each eye, it may be asked, why is it we do not see *double* when we use both eyes? This question is not difficult to answer. When we fix our eyes upon an object, each eye arranges itself in a particular manner. Thus, let B C be the

two eyes (fig. 107), and A the object. Draw A*a*, A*a* through the centre of the crystalline lens, and at right angles to the convex surfaces. These lines are called the *optic axes*, and the angle between them, *a*A*a*, the *optical angle*. The eyes adjust themselves so that the optic axes intersect each other *at* the object. In consequence of this, a precisely similar image of the object is formed in each eye, and therefore a precisely similar impression of the object is conveyed to the mind. If either eye be prevented from thus adjusting itself by slight pressure on the eye-ball, double vision results. Hence persons who *squint* have always double vision. It thus appears that single vision arises from the circumstance that the image is cast upon *corresponding* parts of the retina in both eyes.

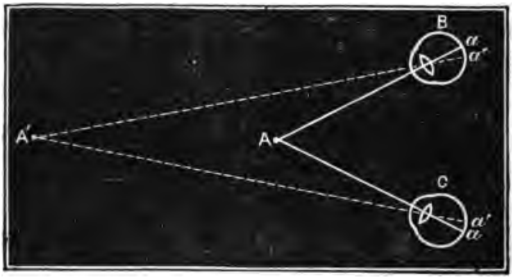


Fig. 107.—Cause of Single Vision.

If, whilst the eyes are directed upon a small object at A (fig. 107), there is another object A′ placed beyond, that latter object will be seen double. This results from the images in the two eyes being thrown upon *different* parts of the retina. Thus, the image in B is formed on the *left* of the optic axis, and that in C on the *right*. If the eyes be directed upon A′, then A will be seen double for the same reason.

It is possible to have a double image with *one* eye. For this purpose, make two small holes with a pin in a card about $\frac{1}{8}$ of an inch apart; place the card close to one eye, and look through these holes at a round spot of ink on a piece of white paper, two spots are seen thus (⦁⦁), the circles being the holes which appear to overlap. The one spot, however, is seen to be much fainter than the other.

117. Accommodation of the Eye.—A distinct picture of an object by a lens is only obtained when the lens is properly adjusted in reference to the object and screen. If, whilst the lens and screen are kept in position, the object be placed nearer or farther away, the image becomes indistinct. Now, in the case of the eye, experience teaches us that objects are seen well enough, though their distances may vary considerably. It follows, therefore, that the eye must have the power of accommodating itself to the distance at which an object may be situated. This accommodation is effected by the *movements* of the crystalline lens—the suspensory ligaments are such as to cause a slight movement of the lens either forwards or backwards, according to the distance of the object looked at, whilst at the same time, from its elasticity, its curvature is also changed, the anterior surface especially being affected. The range of accommodation is, of course, limited.

118. Long and Short Sight.—In advanced life the eye loses its power, and becomes incompetent to bring the rays to a focus upon the retina at the ordinary distance of distinct vision. This condition of the eye, which is common to most elderly persons, is termed "far-sightedness."

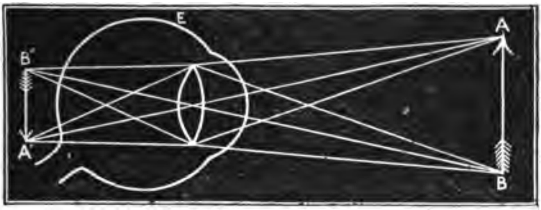


Fig. 108.—LONG-SIGHT.

Let E be such an eye, and AB the object (fig. 108); the rays from it tend to converge to a focus *beyond* the retina, and an image of the object would be formed at A′ B′; the rays, therefore, which fall upon the retina are in a *state of separation*, each produces a picture of its own, and indistinct vision is the consequence. The defect may be so far remedied by placing the object at a greater distance from the eye, so as to give the rays a less degree of divergence, and thus enable

the eye to bring them to a focus upon the retina. Hence, old persons have a greater difficulty in seeing distinctly near objects than those at a distance. But, should the eye be too weak even to accomplish this, a convex lens or glass must be used, just of sufficient power to aid the eye towards the proper convergence of the rays.

Some eyes again have too much convergent power, that is, they bring the rays to a focus in *front* of the retina. This condition of the eye is called "short-sightedness." Thus, if A B be the object placed before an eye of this kind (fig. 109), an image of A B is formed in the interior of the eye at A′ B′; the rays therefore, in this case, also fall upon the retina in a scattered state, and indistinct vision ensues. If the object be placed nearer the eye, the divergence of the rays is increased, and may be made such as just to enable the eye to form the image upon the retina. Hence short-sighted persons can see near objects with greater distinctness than distant ones.

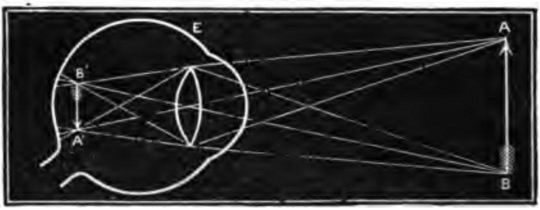


Fig. 109.—SHORT-SIGHT.

The remedy for short-sightedness is to provide a concave glass of such diverging power as to give the eye sufficient work to do to converge the rays to a focus on the retina.

Spectacles.—It is a matter of great importance, in selecting spectacles, to obtain that degree of convergence or divergence, as the case may be, which enables the eye to perform its functions aright. It is a common mistake to use too powerful glasses—this is prejudicial, as it tends to weaken the natural eye-sight. The persistent use of a single eye-glass is also deleterious, as tending to cause a difference in the natural power of the two eyes.

Spectacles have generally numbers attached to them, expressing their principal focal lengths in inches. The particular

number of convex spectacle may be obtained from the following formula:

Taking 12 inches as the distance of distinct vision for a normal eye, let d be the distance of distinct vision for a "long-sighted" eye, and n the number required, then $n = \frac{12\,d}{d - 12}$.

In the case of "short-sight," the formula is $n = \frac{12\,d}{12 - d}$.

In ordinary spectacles, the field of vision laterally is somewhat limited. To increase it and thus prevent the head from being moved round unnecessarily, the glasses more recently used are concavo-convex lenses. In order, also, that objects at a distance may be seen equally well with those that are near, one part of the glass is made to have a less curvature than the other part. Spectacles provided with such glasses are called "periscopic."

119. Size of Objects—Visual Angle.—The size of the image of any external object depicted on the retina, depends upon the distance of the object from the eye. Thus, let R represent the retina, and L the crystalline lens, A B the object (fig. 110). The size of the image for that distance of the object is *ab*. If, now, the same object be placed at A′ B′,

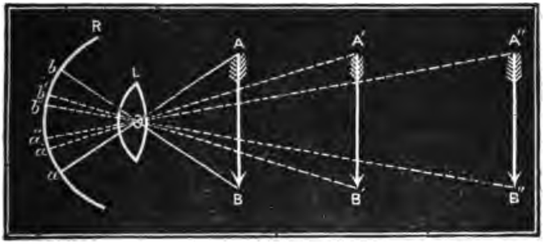


Fig. 110.—Varying Image of the Same Object.

its image becomes reduced to *a′ b′*, and if placed further away still at A″ B″, *a″ b″*. In a word, the greater the distance of the object the smaller the image. The angle A O B is called the *visual* angle; in general, it is *the angle which the object subtends at the centre of the crystalline lens.* It thus appears that, *so far as the eye is concerned,* the size of an object depends upon the magnitude of the visual angle.

If, therefore, we have any number of objects, A, B, C, etc. (fig. 111), having the *same* visual angle, these, though in reality very different in magnitude, will cast the same size of image on the retina.

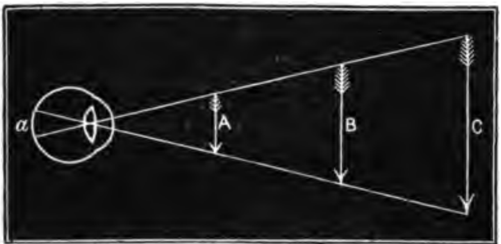


Fig. 111.—Image the Same for Different Objects.

It thus appears that, were we to judge of the *size* of an object from the size of the picture formed on the retina, we would judge erroneously. How then, it may be asked, can we form so correct a judgment of the size of objects? The reason is, that we learn by habit and experience to take into account the *distance* at which the object may be placed. A child, for instance, placed near us may appear under the same visual angle as a man at some distance off, yet we are in no way misled as to their comparative sizes; we do not imagine that the child is as tall as the man. We learn by experience to combine, in our judgment, the *distance* at which the child is in reference to the man; and thus it is that we are led to correct the impressions which our eyes of themselves would convey.

120. Persistence of Impressions.—The impression which light makes on the eye is not obliterated *instantaneously;* it continues for a short time after the cause of that impression has ceased to act. Its duration is found to vary with different eyes, and also with the intensity and colour of the light; but, in all cases, its amount is a sensible fraction of a second. If, therefore, a series of distinct impressions be made upon the eye, which succeed each other with sufficient rapidity, these impressions will be blended together and will produce a continuous sensation. This persistence of impression explains the following familiar facts: The glowing end of

a stick which has been thrust into the fire, when whirled rapidly round, gives the appearance of a continuous circle of light. A flash of lightning is seen for a time as an unbroken track of fire in the heavens. A falling star presents a similar appearance. So also, when it is raining heavy, there appear so many lines of water falling to the ground.

On this principle a number of entertaining instruments have been constructed. The *magic disc*, the *thaumatrope*, the *kaleidophone*, the *wheel of life*, the *chromotrope top*, etc., all owe their action to this principle.

121. Irradiation.—This is a phenomenon in virtue of which small objects, when highly illuminated, appear larger than they really are. It results from the spherical aberration of the eye, or from the fact that there is an extension more or less of the image upon the retina beyond its *true* or *defined* outline.

Irradiation explains such facts as the following:—

"A platinum wire, raised to whiteness by a voltaic current, has its apparent diameter enormously increased. The crescent moon seems to belong to a larger sphere than the dimmer mass of the satellite which it partially clasps. . . . The white-hot particles of carbon in a flame describe lines of light because of their rapid, upward motion. These lines are *widened* to the eye; and thus a far greater apparent solidity is imparted to the flame than in reality belongs to it." * So also a bright star, such as Sirius or the Dog-star, appears larger than it really is.

122. Defects in the Eye.—Viewed as an optical instrument, the eye is by no means perfect. There are certain defects which it appears to possess. The iris, in limiting the passage of light through the central part of the crystalline lens, so far obviates *spherical aberration*, but it is not wholly prevented; there is always a certain amount of luminosity surrounding the images of objects cast upon the retina, detracting, therefore, from the clearness of definition.

"There are also a number of minute fibres, corpuscles, and folds of membrane which float in the vitreous humour, and are seen when they come close in front of the retina, even under the ordinary conditions of vision. They are then called *muscæ*

* Tyndall's *Notes on Light*, pp. 26, 27.

volitantes, because, when the observer tries to look at them, they naturally move with the movement of the eye. They seem continually to flit away from the point of vision, and thus look like *flying insects*. These objects are present in every one's eyes, and usually float in the highest part of the globe of the eye, out of the field of vision, whence, on any sudden movement of the eye, they are dislodged, and swim freely in the vitreous humour. They may occasionally pass in front of the *fovea centralis*, and so impair sight. It is a remarkable proof of the way in which we observe, or fail to observe, the impressions made on our senses, that these *muscæ volitantes* often appear something quite new and disquieting to persons whose sight is beginning to suffer from any cause; although, of course, there must have been the same conditions long before." *

Again, the eye suffers from *chromatic aberration* (see Art. 132). This does not sensibly interfere with ordinary vision, but the fact is beyond doubt, proved as it has been in several ways.

123. The Eye Deceived.—The eye is liable to delusion. The accompanying combination of lines (fig. 112) shows this.

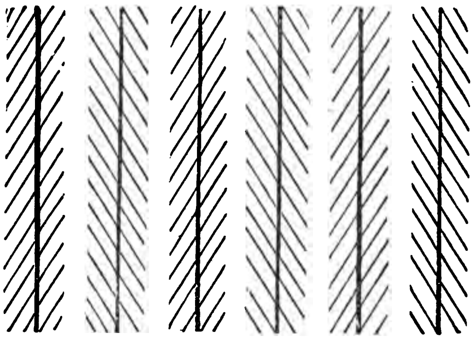


Fig. 112.—The Eye Deceived.

The strong dark lines are drawn strictly parallel to each other, yet they appear to approach each other at the bottom and top alternately, when the book is held in the ordinary

* Helmholtz, p. 220.

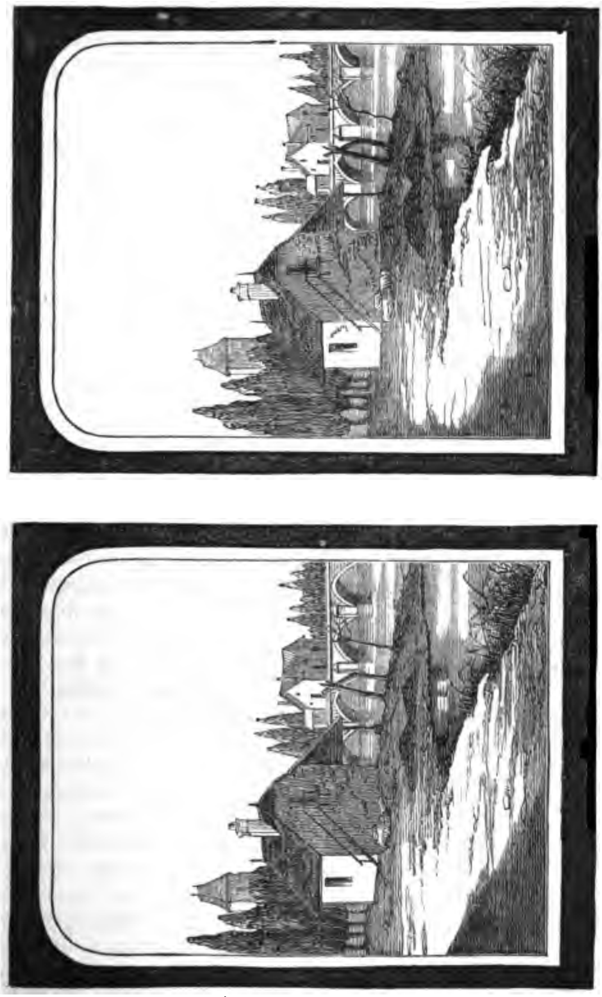


Fig. 113.—Difference in the Pictures of a Stereoscopic Slide.

way. This is in consequence of the presence of the thin sloping lines. That the thick lines are really *parallel* may be tested by applying a pair of compasses, or by sloping the book away from the eyes and looking along the lines, when the thin sloping ones become so far lost to view.

124. Stereoscope.—In looking at any object, the image or picture formed in each eye is *not* the same. For example, if we place a vase before us, there is depicted on the retina of the *right* eye an image of the vase, and on that of the *left* eye also an image of the vase; but the former image is *different* from the latter—a part of the vase is seen by the right eye which is not seen by the left, and a part is seen by the left which is not seen by the right. If, therefore, pictures be taken of the vase corresponding to the views of the individual eyes, these pictures will not be identical. The object of a stereoscope is to *combine* such pictures, and thus by its use there is produced in the mind the same impression as would result were the object actually before us. Fig. 113 will show the difference which subsists between the two pictures in a stereoscopic slide.

The first form of the stereoscope is due to Wheatstone. It consisted of two plane mirrors, so arranged as to reflect to each eye the particular view of the object which belonged to it, and at the same time to make these views coalesce. This is known as the "reflecting" stereoscope.

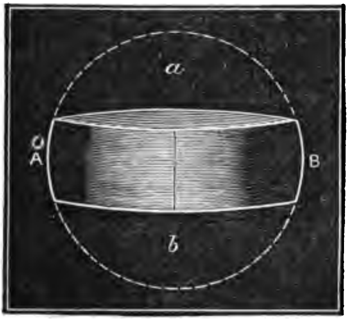


Fig. 114.—Construction of the Glasses.

The most familiar form of the instrument is the "lenticular" stereoscope, invented by Brewster. Its construction and action will be understood from the accompanying figures. A double convex lens (fig. 114) has its sides, *a*, *b*, cut away, the remaining part A B is then cut across at the middle. The two halves are set in the instrument with their edges A, B, in juxtaposition, as in fig. 115.

Now, let C, C′ be the two pictures of the object placed in the focus of the divided lens, the rays, after emerging from the glasses, enter the eyes as if they came from one picture at D; in other words, the two pictures will overlap or be blended together at that point, and thus there is produced in the mind the impression of *solidity* or *relief.*

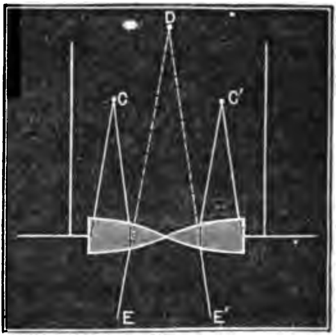


Fig. 115.—STEREOSCOPE IN SECTION.

CHAPTER. V.

DISPERSION—PROPERTIES OF SPECTRUM.

125. Dispersion of Light.—When a beam of solar light is made to pass through a prism, the beam is not only refracted, but it is also decomposed or broken up into so many constituent parts—a phenomenon which is called *dispersion.* Newton was the first to discover this. He admitted a sunbeam S, fig. 116, by a small circular aperture in the shutter of a darkened room. Allowing it free passage, an image was formed on the floor at S′, but on intercepting the beam with a prism P, placed as in the figure, he found an elongated image formed on the screen at E, rounded at the ends, and coloured with a variety of tints, the most prominent being (commencing from the lower end), red, orange, yellow, green, blue, indigo, and violet. The image thus formed he called the *solar spectrum.*

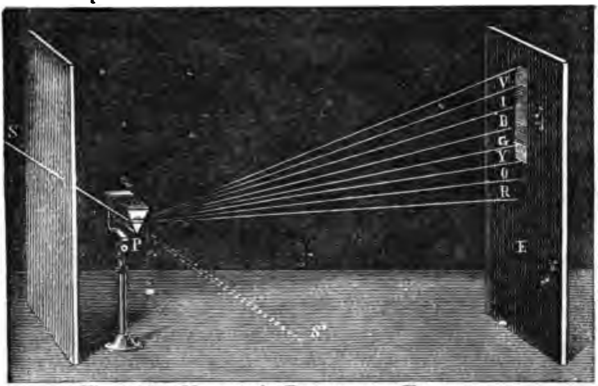


Fig. 116.—NEWTON'S DISPERSION EXPERIMENT.

By this method the coloured spaces, with the exception of e red and violet, are by no means well defined. The

elongated image, in fact, is made up of a series of spectra, which run into, or overlap, each other, and thus in reality an infinite variety of tints is obtained.

In order to obtain a *pure* spectrum, that is, one in which this overlapping is avoided, the beam must be admitted through a very narrow slit, and sent through several prisms in succession, so as the more effectually to separate the colours —even then the mingling of colour is not wholly prevented.

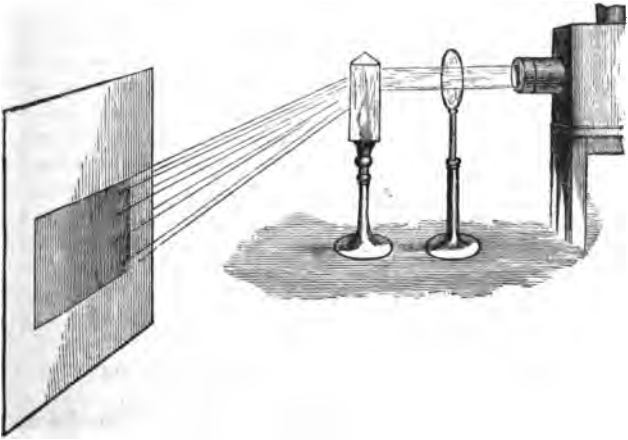


Fig. 117.—CONVENIENT ARRANGEMENT FOR DISPERSION.

The arrangement represented in fig. 117 is a convenient one for exhibiting the spectrum of the electric light. The electric beam, after passing through the narrow vertical slit in the lantern, is received first upon an *achromatic* lens (see Art. 132). It then passes through the prism, which is placed vertically with its refracting edge parallel to the slit, and is adjusted in the focus of the lens. The spectrum is thus exhibited on the screen as a horizontal band of coloured light. The colours are the same, and follow the same order of succession as those in solar light. It is of advantage to adjust the prism, so as to secure the *minimum* deviation of the rays. When a pure spectrum is obtained, and each of the separate colours is made to pass through another prism, whilst the

remainder are intercepted by an opaque diaphragm, no further decomposition takes place—the red rays, for example, give a red image, the yellow, a yellow image, and so on. Hence we conclude that white light consists of these seven colours, and these *only*.

126. Difference of Refrangibility in the Rays of the Spectrum.—The power which a prism seems to possess of unravelling white light, arises from the circumstance that the different colours have different degrees of refrangibility. Thus the red rays being the *least* capable of refraction, undergo the least deviation, the violet rays, being most refrangible, have the maximum deviation, whilst the intermediate rays, possessing degrees of refrangibility between these limits, assume positions in the spectrum accordingly.

The explanation of dispersion by the undulatory theory is a simple matter. The ether waves, generated by the sun, have not the same length; some are shorter than others. In passing through a refracting substance they are all retarded, as we have seen, the long waves, however, to a less extent than the short ones. The amount of deflection, therefore, will be less for the long waves, and greater and greater in proportion for the shorter waves; hence the disposition of the different colours in the spectrum corresponding with the lengths of their waves (see Art. 133).

127. Dispersive Power of Substances.—With the same *kind* of prism, the extent of separation of the colours depends upon the magnitude of the refracting angle—the greater this angle, the greater the dispersion effected. The amount of dispersion also depends upon the substance of which the prism is composed. A glass prism, for example, with a refracting angle of 30°, produces a greater dispersion than a water prism having the same refracting angle. Again, a prism of flint-glass is found to possess nearly double the dispersive power of one constructed of *crown-glass*, the refracting angles being the same. A prism filled with the liquid—the *bisulphide of carbon*—has a still greater dispersive power than one of flint-glass. The form generally given to such a prism is represented in fig. 118. The cork is made fast by a piece of leather placed over it, and secured by string round the neck of the bottle. In experiments

with this kind of prism, the refracting angle ought to be about 45°. If such a prism be placed as in fig. 116, the aperture in the shutter being 2 in. in diameter, the spectrum obtained would be about 8 in. in length, the colours being well separated, except for a narrow space of about 2 in. in the middle.

Fig. 118.—Bisulphide of Carbon Prism.

128. Properties of the Solar Spectrum.—Beyond the limits of the visible spectrum in both directions, there are rays which, under ordinary conditions, do not excite the optic nerve, and are therefore not visible. Their presence, however, may be made manifest in various ways. Thus, if a *thermo-pile* and galvanometer (see Art. 265), be applied to the red space in the spectrum, the deflection of the needle is very small, but if gradually moved away from the red end, the deflection becomes greater and greater, till a point is reached where the deflection is a maximum, indicating therefore the point of greatest heat; passing this point the heat diminishes, and eventually disappears towards a point as far away from the red as the whole length of the *visible* spectrum. Again, by taking a *quartz* prism and shutting off the bright part of the spectrum, the *ultra-violet* rays may be rendered so far visible. This results from the property that quartz possesses of transmitting such rays with greater readiness than glass. It is the violet and ultra-violet rays which are so serviceable to the photographer.

The solar spectrum, therefore, in its entirety may be considered as consisting of three parts, nearly of equal length—the ultra-red, the luminous, and the ultra-violet space. These differ in character from each other: the ultra-red space is rich in *heat* rays; the luminous space in *luminous* rays; the violet and ultra-violet space in *chemical* rays. The degree to which these different powers are exhibited is well indicated by the curves in fig. 119. The extent to which the curves rise above the spectrum serves as an index to

the different powers specified. Thus the maximum heating power is found beyond the extreme red at *a*, the maximum illuminating power in the yellow at *b*, and the maximum chemical or *actinic* power (as it is called) in the violet at *c*.

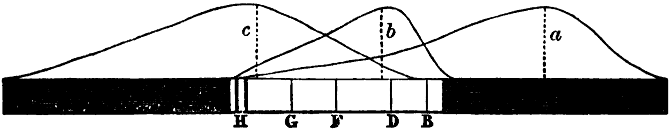


Fig. 119.—Properties of the Solar Spectrum.

129. Calorescence and Fluorescence.—These are terms applied to *the conversion of the invisible rays into visible ones.* The former applies to the ultra-red, the latter to the ultra-violet rays.

(1.) *Calorescence.*—It is possible to sift the solar or electric beam, so as to separate the luminous rays from the non-luminous ones. A solution of alum, for example, transmits the luminous, and arrests the non-luminous rays—whilst, again, a solution of the bisulphide of carbon, mixed with iodine, arrests the former, and transmits the latter. By taking a spherical flask and filling it with the latter solution, and causing the beam to pass through it, the flask, acting like a lens, concentrates the heat rays in a focus, sufficient to explode gun-cotton, or raise a piece of platinum foil to red-heat.

(2.) *Fluorescence.*—Certain substances, both fluid and solid, *fluoresce*, that is, emit a glowing light *in virtue of their absorption of the ultra-violet rays.* A solution of quinine, for example, which is as clear as water, fluoresces with a bright blue colour—a solution of turmeric, which is of a yellow tinge, with a beautiful green colour. The phenomenon was first observed in the fluoride of calcium, which of itself is green, but fluoresces with a fine indigo-violet colour—hence the term *fluorescence*, proposed by Stokes.

From such results we are led to the conclusion that in calorescence the refrangibility of the rays is *heightened*, and in fluorescence *lowered*, so as in either case to bring them within the limits of visibility.

130. Visible Solar Spectrum not Continuous.—The

visible part of the solar spectrum is not *continuous*. There are certain interruptions in its continuity caused by the presence of a number of fine dark lines, running throughout its whole extent, and perpendicular to its length. These were first observed by Wollaston, but were afterwards more accurately studied and mapped out by Fraunhofer, and are hence known as *Fraunhofer's lines*. By sending a solar beam through a succession of prisms, and thus increasing the dispersion, the number of these lines is vastly augmented. As many as 2000 have thus been counted. In some places they are close together; in others, more separate and well marked. Fraunhofer distinguished eight prominent lines by the letters A up to H (fig. 119). The position of these lines, in reference to each other, is found to be the same, whatever kind of prism is used to obtain the spectrum. We shall see afterwards how these dark lines are produced. Meanwhile, it is worthy of remark that they are found also in the spectra obtained from the *reflected* light of the sun, as in the case of the moon and planets.

In the spectra of the electric light, of gas and candle flames, they are absent; in other words, the spectra of such sources of light are continuous.

131. Recomposition of White Light.—Since white light can be broken up into seven different colours, it may naturally be asked, can these colours be so *recombined* as to produce white light? Yes; they can. There are several ways in which this may be effected. The following may be mentioned:—

(1.) By taking another prism of the same refracting angle as the dispersing one, and placing it near the other in an *inverted* position. The first prism decomposes the solar beam; the second reunites the constituent parts of it, and produces a *white* image of the sun.

(2.) By allowing the decomposed beam to fall upon a concave mirror. The coloured rays after reflection are concentrated in the focus of the mirror, and form there a *white* image, which may be received upon a screen.

(3.) By means of Newton's disc. This consists of a disc of cardboard (fig. 120), coloured with the several tints, the different sectors being made to correspond, as far as possible,

with the proportional spaces of the colours as they exist in the spectrum. If this disc be made to rotate rapidly, the colours are so blended as approximately to produce *whiteness.*

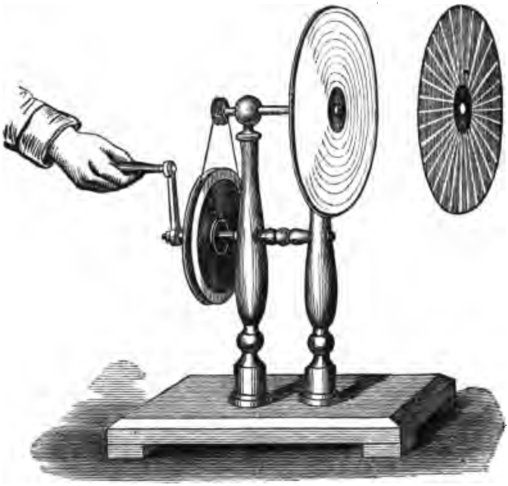


Fig. 120.—NEWTON'S DISC.

132. Chromatic Aberration.—When white light passes through an ordinary glass lens, there is also a certain amount of dispersion—the lens is incompetent to bring the differently coloured rays to a common focus, in consequence of which the

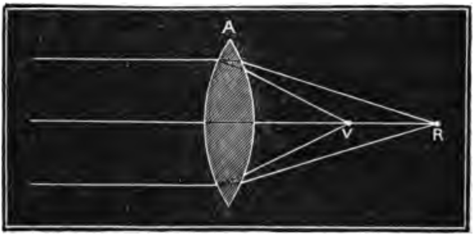


Fig. 121.—CHROMATIC ABERRATION.

image of an object is seen with a coloured border. This lack of power on the part of a lens is called *chromatic aberration.*

Thus the lens A (fig. 121) will decompose the light, and form a *series* of foci instead of one—the red rays being concentrated at R, and the violet ones at V, whilst the intermediate rays are arranged in order.

This defect in a lens is obviated by the combination of a double convex lens of *crown* glass, with a concavo-convex of *flint* glass (fig. 122). The effect of the second lens is to re-blend the coloured rays which the first has produced, and at the same time such an amount of refraction is preserved as to bring the light to a focus.

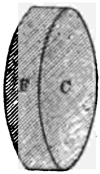


Fig. 122.—Achromatic Lens.

Such a lens is called an *achromatic lens.* The particular curvature which the glasses ought to have, so as to give as perfect achromatism as possible, may be calculated mathematically, but in ordinary practice they are determined by trial. The glasses are cemented together by Canada balsam.

Achromatic lenses are used in the more perfect optical instruments. An achromatic telescope, for example, is one which is provided with such lenses.

CHAPTER VI.

COLOUR—SPECTRUM ANALYSIS.

133. Doctrine of Colour.—Colour is not an *inherent* quality in a body. It arises from the treatment, on the part of the body, of the light which falls upon it.

"Natural bodies possess the power of extinguishing, or, as it is called, *absorbing* the light that enters them. This power of absorption is *selective*, and hence, for the most part, arise the phenomena of *colour*. When the light which enters a body is *wholly* absorbed, the body is black; a body which absorbs all the waves equally, but not totally, is grey; while a body which absorbs the various waves unequally is *coloured*. Colour is due to the extinction of certain constituents of the white light within the body, the remaining constituents, which return to the eye, imparting to the body its colour.

"It is to be borne in mind that bodies of all colours, illuminated by white light, reflect white light from *their exterior surfaces*. It is the light which has plunged to a certain depth within the body, which has been *sifted* there by elective absorption, and then discharged from the body by interior reflexion, that, in general, gives the body its colour. . . .

"A body placed in a light which it is incompetent to transmit appears black, however intense may be the illumination. Thus, a stick of red sealing-wax placed in the vivid green of the spectrum is perfectly black. A bright red solution similarly placed cannot be distinguished from black ink; and red cloth, on which the spectrum is permitted to fall, shows its colour vividly where the red light falls upon it, but appears black beyond this position. . . .

"Colour is to light what pitch is to sound. The pitch of a note depends solely on the number of aërial waves which strike the ear in a second. The colour of light depends on

the number of ethereal waves which strikes the eye in a second. . . .

"The ether waves gradually diminish in length from the red to the violet. The length of a wave of red light is about $\frac{1}{39000}$ of an inch; that of a wave of violet light is about $\frac{1}{57500}$ of an inch. The waves which produce the other colours of the spectrum lie between these extremes."*

"The colours of transparent media, such as coloured glasses, crystals, resins and liquids, depend upon the greater or less facility with which the several coloured rays are transmitted through their substance. There is no medium known, not even air or the purest water, which allows all the coloured rays to pass through it with equal facility. . . . . The more absorbable any prismatic colour, the more quickly will it become so much reduced in proportion to the rest as to exercise no perceptible colorific action on the eye. And thus it is found that in looking through different thicknesses of the same coloured glass or liquid, the tint does not merely become *deeper* and *fuller*, but changes its character."†

It can be readily understood, therefore, that the colour of a body will depend upon the *kind* of light to which it is exposed. A handkerchief, for example, which appears red in daylight, when exposed to the yellow light of spirits of wine mixed with salt, has its tint completely changed. So also certain kinds of paper-hangings have their aspect altered when lit up by gas.

134. Complementary Colours.—One colour is said to be *complementary* to another, when in combination with that other it produces white light. Thus red is complementary to the colour resulting from the mixture of the remaining constituents of the spectrum, or to greenish blue; yellow to indigo blue, and so on.

135. The Rainbow.—This phenomenon is caused by drops of rain acting like prisms in decomposing the solar beams. It is witnessed, as is well known, only when the sun is within a certain altitude above the horizon, and when rain is falling *between* the observer and the part of the sky opposite to the sun.

* Tyndall's *Notes on Light*, pp. 35, 37. 38.
† Herschel's *Popular Lectures*, p. 263.

It may also be observed in the spray of waterfalls, and often as a complete circle of coloured light when the position of the sun is favourable.

It is not difficult of explanation:—The solar rays which fall near the top of the drops are refracted, and such of them as are incident at the back, within the *limiting angle*, are totally reflected. On emerging, the rays are decomposed into their constituent colours, most of which proceeding in a state of divergence do not affect the eye. At *certain* angles, however, the emergent coloured rays proceed in parallel directions, and therefore become visible. Let A and B (fig. 123) represent two rain drops, S, S, the solar rays. On emerging from the drops the rays are decomposed, and such of them as emerge in *parallel* directions affect the eye. The rays from the drop A being red rays, and those from B being violet rays, these meet at some point O, enter the eye there, and produce their respective impressions. The drops between these in like manner transmit the intermediate colours, and thus a perception of the seven colours is conveyed to the eye.

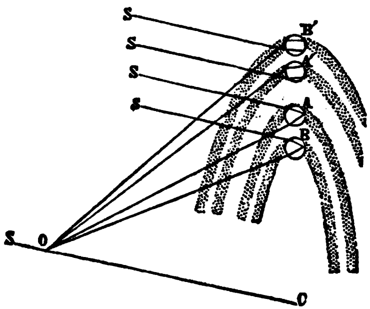


Fig. 123.—The Rainbow.

To understand the *bow-shape*, conceive a line *sc* drawn from the sun through the eye of the observer, and produced to the sky. Further, conceive a line drawn from the eye, making an angle of 42° 30′ with the former line, and moving round it—this line will pass through *all* the drops which are capable of transmitting parallel beams of red light, and hence an *arc* of red light will be seen *uppermost*. In like manner, if another line be conceived drawn from the observer's eye at an angle of 40° 30′ with the first line, and move round it, this one will strike the drops which transmit the violet light. The angles at which the other colours are transmitted are intermediate to these limits, and hence a band of light,

coloured with the several tints of the spectrum, is seen projected on the opposite sky. The extent of the arch depends upon the sun's altitude; it is greatest when the *sun is in the horizon.* In this case, the observer, if situated on a high mountain, may see almost a complete circle.

The bow, just explained, is called the *primary* bow, to distinguish it from another which is seen to accompany it when the sun is sufficiently low in the sky, and which is called the *secondary* bow. This results from the solar rays, which enter near the *bottom* of the drops. They undergo two refractions and two reflexions (fig. 123) in passing through the drops. The secondary bow is above the other, and has the *violet* band uppermost; it is also fainter, in consequence of the greater loss of light by the two reflexions.

136. The Spectroscope.—This intrument has been devised for the purpose of analysing the rays of light emanating from any luminous source. A convenient form of it is represented in fig. 124; it is the form known as the "direct-vision spectroscope." It consists of three tubes which can be screwed on to each other, and which, when the instrument is unused, can be packed into a suitable box. S is a vertical slit, the width of which can be regulated by the screw D. A narrow pencil of light being thus admitted, falls upon the lens L, so adjusted as to have the slit in its principal focus. The parallel emergent beam then passes through a series of prisms in the central tube AB, and undergoes dispersion.

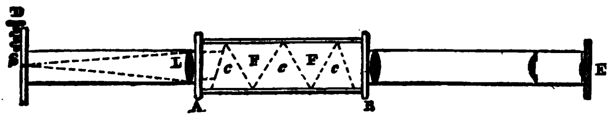


Fig. 124.—Direct-vision Spectroscope.

The prisms F, F are constructed of flint-glass, *c*, *c*, *c* of crown-glass, an arrangement which causes a minimum of deviation in the dispersed beam. The spectrum thus formed is viewed by the telescopic tube BE, which has a compound eye-glass, capable of being moved out for the purpose of focal adjustment. The instrument can be fixed in a stand, and

thus the spectra, from different sources of light, can be carefully examined.

137. Results of Investigation with the Spectroscope.—The main results obtained by the spectroscope are as follow:—(1) *Solid and liquid bodies, in a state of incandescence, give out continuous spectra.* The electric light, the lime light, molten iron, are examples. The temperature of the substance affects the character of its spectrum, but does not break its continuity. Thus iron at a red-heat gives out only the red rays, but as the temperature rises, the other colours make their appearance until a white-heat is attained, when the spectrum becomes complete. (2) *Glowing vapours and gases give out spectra with bright lines on a dark background, and these lines are different for different substances.* In the frontispiece are exhibited some specimens of these spectra. The position of the coloured lines is also indicated in reference to the chief lines of the solar spectrum. It is found that an increase of temperature does not affect the position of these lines, but only adds to their brilliancy. Hence it is possible that lines may become revealed by intense heat, which might escape observation at lower temperatures. This is the foundation of "spectrum-analysis" (so called). (3) *When the light from any luminous body is made to pass through a gas, such rays are absorbed by the gas as it would itself emit when rendered incandescent.* Thus, for example, let the electric light pass through sodium vapour, on its way to the slit of the spectroscope, a *dark* line will be seen on the spectrum corresponding exactly to the position of the yellow line D in the sodium spectrum (No. 2, frontispiece). This is Kirchhoff's discovery, and forms the clue towards the revelation of the constitution of the heavenly bodies.

138. Spectrum Analysis.—This method consists in revealing the chemical elements or constituents of a body by the character of its spectrum when reduced to a state of glowing vapour. Each substance, as stated above, has its characteristic line, or group of lines. Even if the substance be compound in its nature, each constituent will invariably reveal its own peculiar line or lines, so that the resulting spectrum requires only to be minutely examined, in order that its elements may be individualised.

Having made ourselves acquainted, therefore, with the spectra of all the known chemical elements, should any new line or lines be revealed in the examination of a substance, there is positive evidence afforded that some new element is present. In this way it was that Bunsen and Kirchhoff, the founders of the method, discovered two new metals, caesium and rubidium, which had previously been unknown to chemists; and, subsequently, other investigators added thallium and indium to the list.

"The spectrum method of analysis is distinguished from ordinary chemical methods by its extreme delicacy. The three-millionth part of a milligramme of a salt of sodium, an imperceptible particle of dust to the naked eye, is yet capable of colouring the flame yellow, and of giving the yellow line of sodium in the spectroscope. More than two-thirds of the surface of the earth are covered by sea, which contains sodium chloride, or common salt. When waves are raised by the storm, and their foaming summits are carried away, fine particles of salt are mingled with the air, and carried over the land; common salt is consequently distributed through the whole atmosphere in the form of a fine dust. On account of this almost constant presence of sodium chloride, it is scarcely possible to obtain a flame which does *not* exhibit the yellow line of sodium. It is only necessary to shake a handkerchief on the table, or to close a book sharply, to make the dust which escapes colour the adjoining Bunsen's flame yellow, and to make the sodium line appear in the spectroscope." *

139. Constitution of the Heavenly Bodies—Applications of Spectrum Analysis.—Spectrum analysis is not only of use to the chemist in the way of unravelling the composition of substances, but is of signal service also to the astronomer. By its means we are made aware of the constitution of the sun, stars, nebulæ, etc. We will explain, shortly, how this knowledge is attainable. Every gas or

Every gas or vapour, as we have seen is impervious to those rays, which it would emit when incandescent. Suppose the spectroscope so arranged as to admit the light from a sodium flame through the lower part of the slit and a sunbeam through the

* Lommel on *Light*, p. 152.

upper part; looking into the instrument we should see the two spectra, one above the other, and we should find the position of the yellow sodium line to correspond exactly with the position of the D line in the other spectrum. Introducing, in like manner, in succession the flames of hydrogen, iron, nickel, etc., we should be able to compare the positions of the bright lines of these bodies with those of the dark lines of the solar spectrum, and observe where coincidence occurs. From these observations, therefore, we should be able to infer what vapours are present in the solar atmosphere; for these, by their absorption of the rays from the incandescent sun, have left gaps or dark lines in those places where none should have appeared had they been absent. In this way it has been proved that the sun's atmosphere contains, amongst others, the following metals in a state of vapour—sodium, iron, nickel, copper, zinc, magnesium, and, besides, a large quantity of glowing hydrogen.

The so-called protuberances, or reddish-like prominences, seen round the edge of the sun during total eclipses, are believed to be due chiefly to the presence of hydrogen; when examined by the spectroscope they are found to give, amongst others, the bright hydrogen lines. They cannot be seen in ordinary circumstances, in consequence of the sun's glare, but their presence can be detected even in brilliant sunshine by a particular arrangement of the spectroscope. The method, suggested by Lockyer, consists in using a strongly dispersive instrument, by which the brilliancy of the ordinary spectrum is much diminished. This hydrogen atmosphere is proved by Lockyer to have an average depth of about 5000 miles, and to reach, in some cases, to the height of 70,000 miles. The heavings and surgings of this vast hydrogen ocean, moreover, are such as to indicate, in some instances, a velocity of 120 miles per second.

The moon and planets are seen in virtue of their reflecting the light of the sun. If, therefore, they are not surrounded with atmospheres, they should give spectra similar to the solar spectrum. The moon exhibits the *same* lines, hence the conclusion that she possesses little or no atmosphere. The planets again give evidence of being surrounded with an atmosphere, identical, in some particulars, with our own.

As to the stars, which shine by their own light, their

spectra afford evidence of the presence of sodium, magnesium, iron, hydrogen, etc. "No star, sufficiently bright to give a spectrum, has been observed to be without lines. Star differs from star only in the grouping and arrangement of the numerous fine lines by which their spectra are crossed. . . . A comparison of the spectra of stars of different colours suggests that the colours of the stars may be due to the action of their atmospheres. Those constituents of the white light of the star, on which the lines of absorption fall thickest, are subdued, the star being tinted by the residual colour."*

140. Explanation of Fraunhofer's Lines.—We are now in a position to give a satisfactory account of the dark lines in the solar spectrum. Were the light from the sun's *photosphere*, as it is called—the real repository of the light and heat we derive from the great luminary—to come to us uninterrupted, we should have a continuous spectrum, similar to what we derive from the lime or electric light, as a source; but that light, before it reaches us, has to pass through the so-called *chromosphere*, or solar atmosphere, consisting chiefly of metallic vapours; in doing so, the rays are sifted, as it were, certain of them are absorbed by these vapours, and are thus prevented from telling their tale, whilst the residual ones have a free passage. In a word, therefore, the lines of Fraunhofer are cast on the spectrum, just at those places where *absorption* has taken place.

It is worthy of remark, however, that certain of the dark lines are due to the absorptive influence of our own atmosphere—these, for the sake of distinction, are known as the *atmospheric* lines. They result from the constituent elements in our atmosphere, oxygen, nitrogen, etc.

Why certain of the sun's rays should be arrested in their passage through the solar atmosphere, is not difficult to understand. The rays only whose periods of vibration *differ* from those of the vapours which they have to encounter, are permitted a free passage. Those rays again whose periods of vibration *synchronise*, have their energy spent upon these vapours, and thus undergo absorption. The case is analogous to what takes place in the "sympathetic vibration" of sound (Art. 51).

* Tyndall's *Notes on Light*, p. 45.

CHAPTER VII.

OPTICAL INSTRUMENTS.

In this chapter we purpose describing more the *principles of action* of the common optical instruments than going much into detail regarding their construction.

141. Microscopes.—Microscopes are of two kinds, *simple* and *compound*. A *simple* microscope, more commonly known as a "magnifying glass," consists of a double convex lens suitably mounted. The action of such a lens towards this object is shown in fig. 98. The *magnifying* power will evidently depend upon the nearness of the eye to the object; in other words, upon the focal length of the glass. It may be found by adding the "distance of distinct vision" to the focal length, and dividing the sum by the latter. Thus if we take 10 inches for the former, and use a glass with a 2-inch focus, the magnifying power will be $\frac{10+2}{2} = 6$, that is, the image will be six times as large as the object.

A *compound* microscope consists essentially of two glasses, the one next the object is called the *object* glass, or *objective*, the other the *eye*-glass or *ocular*. Its action will be understood from fig. 125. The small object *ab* being placed a little beyond the principal focus F of the objective C, an inverted enlarged image of it is formed at AB in the conjugate focus. If, now, the ocular D be so adjusted as to have this image between *its* principal focus F′ and itself, the image AB will be further magnified to A′B′. Thus the object *ab* is *twice* magnified. The objective has a much shorter focal distance than the ocular, and in order to adjust the instrument to objects of varying size, the objective is fixed in a tube which is capable of sliding up or down inside that containing the ocular. In the best instruments, objectives of

different power are provided, fixed in small tubes, which can be screwed on to the end of the sliding tube according to the strength desired. In this way the magnifying power of the instrument may vary from 30 to 500, or even beyond.

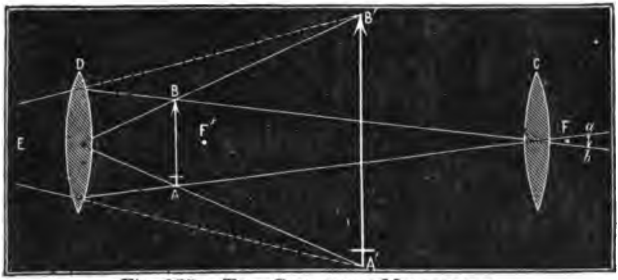


Fig. 125.—The Compound Microscope.

The eye-piece is usually formed of several glasses, for the purpose of securing greater distinctness in the image, but their combined action is the same in principle as that of a single ocular, such as has been described. The glasses are all made achromatic. Sometimes two tubes are used, adapted to the two eyes, and made to converge upon the single tube containing the objective. This is a convenient arrangement for physiologists and others who are much engaged in microscopic investigation.

142. Telescopes.—There are two classes of telescopes, the *refracting* and *reflecting*.

Refracting.—(1.) The common *astronomical* telescope is of this kind. Fig. 126 shows its construction. It is much the same in principle as the compound microscope. The chief difference lies in this—that the objective has a much longer focus than the ocular.

The distant object AB has an inverted image, formed by the objective at A′B′, somewhat beyond the principal focus F. This image is magnified by the ocular in the same manner as before, and thus the distant object appears to have the size A″ B″. It is the case that A″ B″ is really smaller than AB, but owing to its nearness to the eye, as contrasted with the distance of the object, in other words, to the difference in the size of the visual angle, the remote object appears

Fig. 126.—The Astronomical Telescope.

magnified. The magnifying power will evidently depend upon the size of the image A'B'—the greater the distance from the objective, or which is the same thing, the greater the focal length of the objective the larger this image. Hence in a powerful telescope of this kind the objective used must have a long focal distance, which, of course, implies a tube of considerable length. For the purpose of adjustment, the tube containing the eye-piece slides into the other. In order to have the image bright and distinct, a large objective is required; in the telescopes used in observatories, it is not unfrequent to have objectives 16 inches in diameter, with a focal length of about 24 feet. A few years ago a large instrument was constructed at York; it is 32 feet long, and has an objective of 2 feet 1 inch in diameter.

(2.) The image of an object, as seen in an astronomical telescope, is evidently *inverted*. This, of course, is no drawback in viewing a celestial body; but in a telescope adapted for terrestrial objects, it is desirable to have this inversion corrected. Accordingly this is done in the *terrestrial* telescope. It is usually effected by introducing two additional glasses C, D, of the same strength (fig. 127), into the tube containing the ocular. The action of the instrument is as follows:—An image of the object AB is formed at *ab* in the conjugate focus, inverted. This image being placed in the principal focus of the lens C, the rays, after emergence, pass in parallel directions,

and cross each other at the aperture of a diaphragm *d*, interposed to arrest stray light; they then fall upon the lens D, and on emerging from this, form an erect image *a'b'* in its principal focus. Lastly, this image is magnified by the ocular in the same manner as before. To adjust the instrument for objects at different distances, the compound ocular is placed in one tube, and the objective in another. Sometimes a middle tube is introduced—all sliding into each other, to focus the instrument more perfectly.

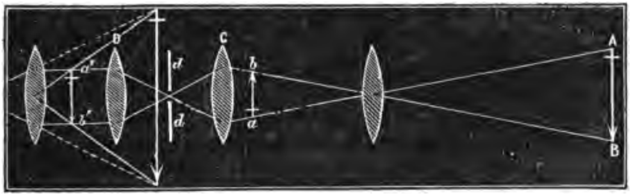


Fig. 127.—The Terrestrial Telescope.

(3.) The *Galilean* telescope, so named from its inventor, Galileo, is also adapted to give erect images. It is represented in fig. 128. The objective is a double convex lens,

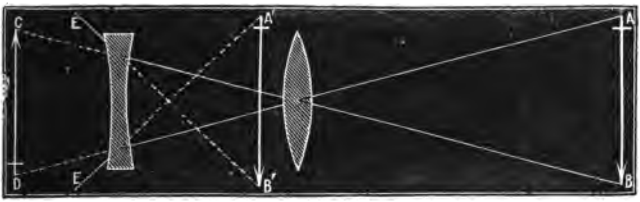


Fig. 128.—The Galilean Telescope.

and the ocular, a double concave. To have a magnifying effect they must be placed at a distance from each other, about equal to the *difference* between their focal lengths; and in order to effect this adjustment for different objects, they are fixed in separate tubes. The action is this:—An image of AB would be formed by the objective at CD, inverted,

but the rays, before concentration, are caught by the ocular, and on emerging from it, become divergent, enter the eye as if they came from an object A′B′, larger than the original object, but in the same position. By an instrument of this kind, though its magnifying power is necessarily small, Galileo was enabled to make some interesting discoveries in astronomy.

By the peculiar adjustment of the glasses, the instrument can be put into small compass, hence the application of the principle of construction in the "opera-glass," and in the so-called "field-glass." Both instruments are Galilean telescopes.

143. Reflecting Telescopes.—(1.) The first form of reflecting telescope was invented by Newton, hence called "Newton's telescope." It consists of a tube closed at one end by a concave spherical reflector (fig. 129). The open end being directed to the distant object, the rays of light from it, which enter, are reflected by the mirror R, and would form an image in the focus at $a'b'$; but before convergence they fall upon a small plane reflector, making an angle of 45° with the axis of the tube, by which they are made to converge in a focus at ab, forming an image there.

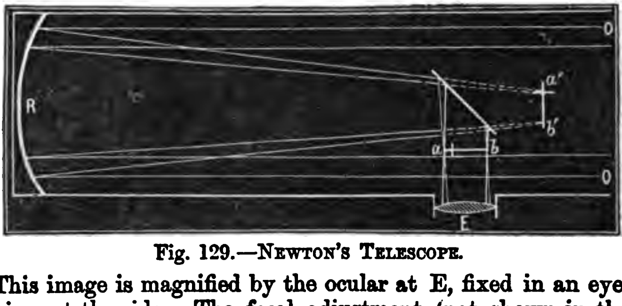


Fig. 129.—Newton's Telescope.

This image is magnified by the ocular at E, fixed in an eye-piece at the side. The focal adjustment (not shown in the figure), is effected by connecting the small mirror with the eye-piece, both being capable of a limited movement along the side of the tube.

(2.) The "Gregorian telescope" differs from Newton's in being a *front*-view telescope, as in the refracting form. The

reflector R (fig. 130), has a circular aperture in the centre, opposite which are fixed the eye-tube, on the one side, and at some distance on the other, a small concave reflector *n*.

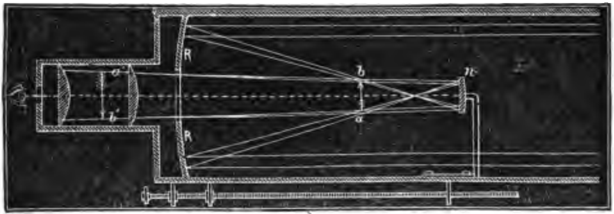


Fig. 130.—THE GREGORIAN TELESCOPE.

The principle of action is as follows:—An inverted image is formed of the remote object by the reflector R at *ab*, the rays thereafter crossing each other fall upon the small reflector *n*, and are concentrated a second time, with the aid of a lens at *a′b′*; that image having now the same position as the original object is magnified, as before, by the ocular. The small reflector *r* is made fast to a rod which runs along the side of the tube, and by which the focal adjustment may be effected.

(3.) The "Herschelian telescope" is a modification of Newton's. The reflector is slightly inclined to the side of the tube (fig. 131). The image of the object is thereby

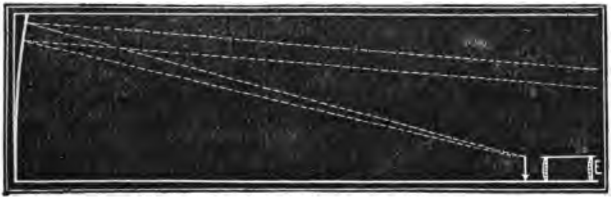


Fig. 131.—THE HERSCHELIAN TELESCOPE.

formed close to the side, where accordingly the ocular is placed. The tube is 40 feet long, and the reflector has a diameter of 4 feet 2 inches.

Lord Rosse's telescope has the same construction, but its dimensions are greater. It is 54 feet in length, with a reflector 7 feet in diameter. The construction of these large

instruments led to some important discoveries in astronomy. The reflectors in these instruments consist of *speculum* metal, a compound of tin and copper mixed in certain proportions. From the necessary labour in their manufacture, they are expensive. In recent years specula of silvered glass have been successfully introduced.

144. Camera Obscura.—This instrument is constructed in different ways, but in all the purpose is the same, viz., to cast upon a screen a real image of an external object by means of a convex lens. The most familiar form is that used in photography. Fig. 132 exhibits a form adapted for viewing a distant landscape, or, if required, to sketch it off.

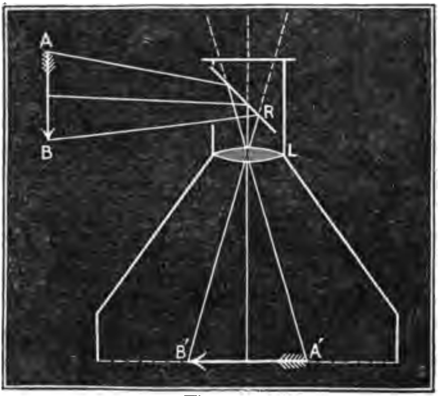


Fig. 132.

It consists of a sloping, wooden box, blackened inside, to obviate irregular reflexion, at the bottom of which is placed a sheet of paper. At the top there is a small cubical box, formed of two parts, one of which slides into the other, for the purpose of focal adjustment, and which contains respectively a plane reflector and a double convex lens. The action of the instrument is this: The rays from some distant object, A B, are reflected by the mirror towards the lens; the lens concentrates these rays into a focus and an image A′ B′ is thus formed upon the paper. There are two apertures through one of which the picture is viewed, and through the

other the hand may be thrust for the purpose of sketching it off.

145. Camera Lucida.—This instrument was invented by Wollaston. It consists of a small quadrilateral prism P (fig. 133), mounted in a brass case, and fixed by a movable joint to an upright rod, about a foot in length, which is provided with a screw clamp at its other end, to attach it to a drawing board. The prism being adjusted as in the figure, the rays from an object A B, on entering it nearly perpendicular to the vertical face, are totally reflected at the first sloping surface, and being again totally reflected at the second, enter the eye as if they came from a real object at *a b;* in other words, an image of A B is seen at *a b,* cast upon the drawing paper. To enable the eye to see the image and the point of the sketching pencil at the same time, a small disc of metal with a circular aperture is so adjusted as that half the aperture covers the glass, whilst the other half is kept free. In this way, by a little practice, a faithful sketch of any landscape may be obtained.

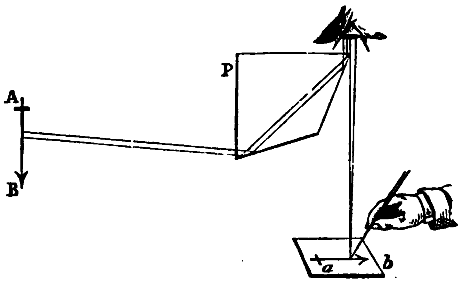


Fig. 133.

146. Magic Lantern.—The construction and principle of this instrument will be understood from fig. 134. The lamp L is placed in the focus of a concave reflector R; the rays from it, after reflexion, are condensed by the lens A upon the glass slide C, on which the picture is painted. An image of the illuminated picture is then formed by the lens B, and thrown upon the screen in a darkened room. The lens B is fixed in a tube which slides into the other, and its focus

can therefore be adjusted to different distances. From what we have seen in regard to the formation of an image by a lens, the slide C must, of course, be introduced in an inverted position. The image on the screen is magnified as many times as the distance of the screen from B contains the distance of C from B.

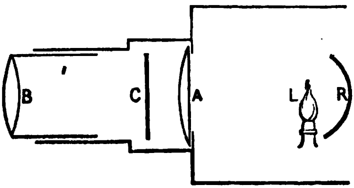


Fig. 134.

Dissolving views are produced by having two similar magic lanters, placed side by side, and directed towards the same part of the screen. A metallic diaphragm is placed before the lanterns, and is so arranged as gradually to close the aperture of the one lantern, whilst that of the other is being opened. By this artifice a pleasing variety of effect is obtained.

The "Solar Microscope" acts on the same principle as the magic lantern. A circular aperture is made in the shutter of a darkened room; a plane reflector is placed outside to reflect the solar rays through the aperture. These are concentrated by two or three converging lenses, on the small objects to be examined, which are thus highly illuminated, and bright magnified images of them are thrown upon the screen.

147. Hadley's Sextant.—This instrument is of great service to the navigator, astronomer, or engineer, inasmuch as it is one of the simplest means of measuring angles. Fig. 135 exhibits its construction. aAB is a brass sector, of which the arc AB is $\frac{1}{6}$th part of the whole circle (hence the name *sextant*). a, b are two plane mirrors set at right angles to the plane of the instrument, of which a is made fast to an arm aC, jointed at the centre, and carrying a vernier at its other extremity, whilst b is fixed parallel to aA, with its *upper* portion unsilvered; T is a small telescope also fixed to aA. Suppose the sun's altitude to be determined. Let Sa be a solar ray, then the arm aC is moved till an image of the sun is seen to coincide with the horizon TH; the altitude θ' = twice the arc AC, or if the half degrees in AC be marked

whole degrees, as is generally done in practice, then $\theta' =$ arc AC. To explain this: Draw the normals to the mirrors, and let α, β, θ express the different angles indicated.

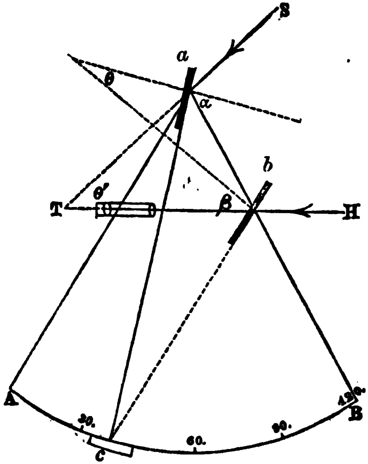


Fig. 135.—HADLEY'S SEXTANT.

$$\alpha = \theta + \beta \therefore \theta = \alpha - \beta,$$

but, $\theta = aCb = AaC =$ arc AC.

Again, $2\alpha = \theta' + 2\beta$

$$\therefore \theta' = 2\alpha - 2\beta = 2(\alpha - \beta) = 2\theta = 2 \text{ arc AC}.$$

Hence if the half degrees in the arc AB be marked whole degrees, then the altitude may at once be read off. The angle subtended by any two objects can, in like manner, be determined by this instrument.

CHAPTER VIII.

INTERFERENCE OF LIGHT—DIFFRACTION.

148. Interference.—We have seen (Art. 32) that two systems of sonorous waves meeting may so affect each other as to produce *silence*. We are now to see that two rays of light or two systems of ethereal waves may, by their union, cause *darkness*.

To understand how this is possible, let us refer to water-waves. Suppose a series of waves to be generated on smooth water by a stone dropped from a height, and that a second series is generated in the same way from the same centre of disturbance, after such an interval of time as that the crests and troughs of the one system meet the crests and troughs of the other system, we can imagine that, under these circumstances, an increased agitation of the water ensues; in other words, the water particles acquire a greater amplitude. But now, let the second series follow the first after such an interval as that the crests of the former are opposed to the troughs of the latter, then at the points of junction, a partial destruction of the motion of the water particles must necessarily take place, and the water there and beyond will, ere long, be brought to rest.

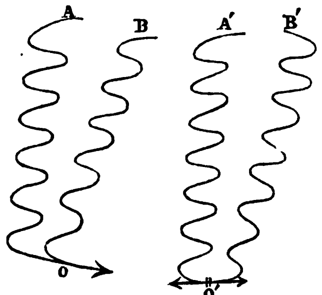


Fig. 136.—Coalescence and Interference of Waves.

To apply this reasoning to light, let A and B be two systems of ethereal waves (fig. 136) of the *same* periodicity, and in the *same* phase of vibration. Meeting

at the point O, they would produce a double motion on a particle of ether there, that is, there would be an increase of intensity in the light. On the other hand, let the two systems be in *opposite* phase as at A′B′. Then, by their union at O′, the particle of ether would be as much urged in the one direction by A′ as it would be urged in the opposite direction by B′, the particle therefore would remain at rest, and hence a destruction of light would occur. Such is the phenomenon of "interference." It follows from what has been stated that interference will occur when one system differs from another by an *odd* number of semi-undulations—the same as what holds good in the case of sonorous waves.

149. Fresnel's Experiment.—This experiment affords a striking proof of the phenomenon of interference. A solar beam is admitted through an aperture in the shutter of a darkened room—the aperture being closed, say, with red glass, to make the light homogeneous. The beam then passes through a lens L of short focal distance (fig. 137), and is

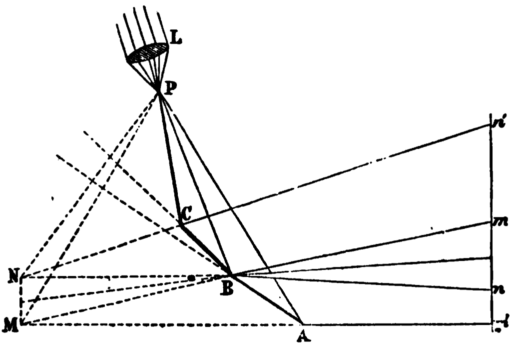


Fig. 137.—Fresnel's Experiment.

concentrated in a focus at P, whence the light diverges and falls upon two metallic reflectors AB, BC, placed at a very obtuse angle, which cast it on a screen. The light reflected from the mirrors proceeds as if it came from two luminous centres M and N; the divergent cones M*mm*′, N*nn*′, encounter each other, and within the common surface *mn* are observed a suc-

cession of dark and red lines. If either mirror be covered with an opaque diaphragm, the dark lines disappear, and the screen presents a uniformly red tint.

If *white* light be used in this experiment, a succession of coloured bands is produced in the space *m n*. These result from the fact that each colour of the spectrum produces a different set of dark lines, and as these sets do not coincide, the dark lines due to one colour are illuminated by the other colours.

Taking this apparatus into a darkened room, and using a spirit lamp with salt sprinkled upon the wick, any one placing his eye in the field of the *common* area may see the dark lines, though, of course, not so distinctly, owing to the feebleness of the light employed.

150. Diffraction or Inflexion.—The statement that light proceeds in straight lines (Art. 75) will now require modification. Under certain circumstances, it can penetrate so far into the true shadow cast by an opaque body, and thus in a measure, as it were, turn a corner. This bending of light round the edges of opaque bodies is known as *diffraction* or *inflexion*.

A small aperture A is made in the shutter of a darkened room for the admission of a sunbeam, reflected through it by a mirror fixed outside, as in fig. 138. The aperture is closed with red glass, and the emergent beam is received upon a lens, L, of short focal distance. The light is thereby concentrated in the focus at O, whence it passes as a divergent cone. If now an opaque body, B, with a sharp edge, be placed in the path of the divergent rays, there is presented on the screen a succession of dark and red bands on both sides of the limit of the true shadow. If blue glass be used to cover the aperture at A, a succession of dark and blue bands is obtained, but *closer together* than in the former case. In a

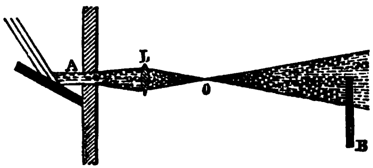
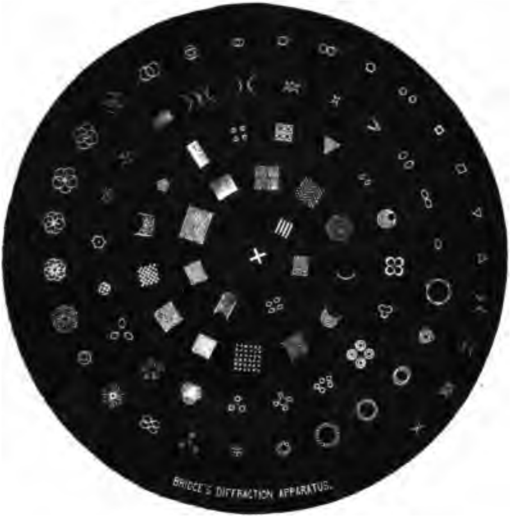


Fig. 138.—Diffraction Experiment.



J. HORSBURGH, PHOTO.
131, PRINCES STREET, EDINBURGH.

word, it is found that the different colours of the spectrum produce different amounts of *packing*, being least for the red light and greatest for the violet. This is due to the fact that the different colours result from different wave-lengths (Art. 133). If white light is transmitted, a succession of *coloured* fringes is obtained.

With the same arrangement, a great variety of beautiful effects is obtained by placing small objects of different shape in the divergent cone. Thus if a small circular disc, say of tin-foil, be so placed, whilst the aperture is closed with red glass, there is presented a red spot in the centre, with a succession of dark and red concentric circles. Here the light seems to have penetrated all round the edges of the little disc, and almost completely extinguished the true shadow. When white light is used, there appears a white centre surrounded by dark and bright rings fringed with delicate colours.

151. Spectrum produced by Diffraction.—The spectrum obtained by the method described in Art. 125 is necessarily influenced by the nature of the material of which the prism is constructed. By diffraction it is possible to obtain a more *natural* spectrum, that is, one in which the arrangement of the colours is in accordance with the inherent properties of the rays themselves, by which they adjust themselves according to their wave-lengths. This may be accomplished in the following way:—A solar beam is admitted into a darkened room through a very narrow slit, and is made to pass through a lens. Behind the lens is adjusted a plate of glass with several parallel lines cut with a diamond at equal distances and very near each other, an arrangement known as a *grating*. The cut lines being practically opaque, they serve as so many diffracting objects, whilst the light has free transmission through the unscratched parts of the glass. On the screen there is presented a white image of the slit, and on either side a beautiful series of spectra, with the violet turned *inwards*, which are isolated and narrow at first, but gradually merge into each other, becoming broader and fainter as they disappear. In these spectra, the lines of Fraunhofer are distinctly visible.

On the separate leaf is represented a positive photograph of "Bridge's Diffraction Disc." It consists of a negative

confined between two glass discs. The diffraction figures, it will be observed, are arranged in a spiral form. The compound disc is introduced into a telescopic arrangement, and the different figures are examined by sun-light reflected from a silvered ball. By bringing them in succession into the field of view, very beautiful effects are obtained.

152. Explanation of Diffraction.—The phenomena of diffraction are due to *interference.* To explain, we must premise that when a wave-system encounters an obstacle, *there is generated at every point a series of secondary or elementary waves;* in other words, *each point becomes a new centre from which waves are propagated,* a principle first established by Huygens, and known as "Huygens' principle."

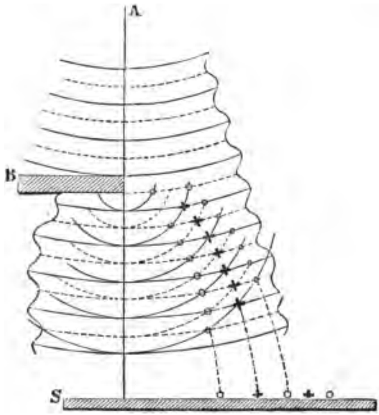


Fig. 139.—Diffraction Explained.

Let A be the source of some homogeneous light, and B the diffracting object (fig. 139), the parts of the waves which fall upon the edge of B give rise to *secondary* waves which proceed as in the figure. These must necessarily meet the direct or original waves emanating from A. If both systems are in the same phase as at the points marked ×, they strengthen each other; but, if they are in opposite phase, as at o, they conflict and so far destroy each other. Accordance or discordance will occur between the two systems, as we have already

according as they differ from each other by an even
>er or an odd number of half wave-lengths. There is thus
>n the screen S an alternation of bright and dark bands,
ı gradually ceases as the secondary waves become weaker.
e partial *extinction* of the true shadow is accounted for
e fact that the secondary wave-systems, generated at the
of the small opaque disc, completely coalesce. The
red fringes, when white light is used, are due to the
ıl interference of the secondary waves, consisting as
do of different wave-lengths, with the original ones.

NEWTON'S RINGS—DOUBLE REFRACTION.

ŀ. **Newton's Rings — Colours of Thin Films.**—The phenomenon known as "Newton's rings" is the result also of interference. To produce them, take a piece of plane glass, upon which place a plano-convex lens of very small curvature (fig. 140). If the apparatus be taken into a dark room, and viewed by the reflexion of monochromatic light, such as that of a spirit lamp with a salted wick, there is seen at the point of contact of the two surfaces a black spot, encircled with a series of alternately yellow and dark rings. They are accounted for thus:—The light in passing through the lens is reflected to the eye not only at the upper surface of the lens, but also at the lower surface of the glass plate; if the reflected rays, which reach the eye, are in the same phase, as, for example, a whole wave-length behind each other, then they coalesce, and give rise to a bright ring; if, on the other hand, owing to the varying distance between the plates, the rays are in opposite phase, say differing from each other by half a wave-length, then discordance ensues, and a dark

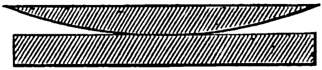


Fig. 140.

Fig. 141.—Newton's Rings.

ring is formed. The dark central spot is due to the fact that *no* reflexion takes place there. If the apparatus is viewed by *transmitted* light, the bright and dark rings change places, in this case the central spot is bright. When exposed to the sun's rays, the rings are coloured. They decrease in breadth from the centre, and at the same time get closer and less distinct, as in fig. 141.

The colours of the soap-bubble, of oil on the surface of water, of lead-scum, of mother-of-pearl, are due to the same cause. Hence also the origin of the colours in tempered steel; and in the so-called "Barton's buttons," which are brass or steel buttons, with delicate cross-lines cut upon them.

154. Double Refraction.—This is the property possessed by certain crystals of separating a ray of light into two parts. Such crystals are called *double-refracting* crystals. This property is possessed in a high degree by Iceland spar (carbonate of lime). This substance crystallises in rhombohedrons. Let $o\,i$, fig. 142 (1), be the incident ray; on entering the crystal it is broken up into two parts $i\,a$, $i\,a'$—the former is called the *ordinary*, the latter the *extraordinary* ray. If a spot of ink on a sheet of white paper be viewed through the crystal it will appear double; and if the crystal be made to rotate, the one image is seen to move round the other. The one which appears fixed is the *ordinary* image, and the other the *extraordinary.* The former is more refracted than the latter, hence it is, in reality, nearer to the eye, though the images of both seem to be cast upon the paper. The ordinary image obeys the ordinary laws of single refraction; the extraordinary image does not, *except in a particular direction.* In other words, whatever be the angle of incidence of the incident ray, it is found that the index of refraction of the *ordinary* ray is constant, its amount in all cases being 1·654; moreover, the incident ray and ordinary ray are in the same plane. The index of the *extraordinary* ray, again, is found to vary between the limits 1·483 and 1·654, according to its direction through the crystal; the *former* value is known as the *extraordinary* index.

To account for double refraction, it is assumed that *the molecular grouping is not uniform in all directions,* and therefore that the *ether has different degrees of elasticity.*

The consequence is, that the light has different velocities in different directions, or is more retarded in one direction than in another, producing thereby different amounts of refraction. In the case of single refraction, as in air, water, and well-annealed glass, the elasticity of the ether is the same in all directions. Hence if the molecules of these bodies are not uniformly distributed, we should have double refraction, and this is really found to be the case in ice and badly-annealed glass.

155. Uniaxal and Biaxal Crystals.—All double refracting crystals possess, in some cases, *one* direction, and in others, *two* directions, in which a ray of light escapes bifurcation. The former are designated *uniaxal* crystals, and the latter *biaxal* crystals.

(1.) *Uniaxal.*—In such crystals the direction along which there is no separation of the ray, coincides, or is parallel to the *crystallographic* axis $a\,x$, fig. 142 (2)—that is, the line joining the oblique solid angles of the crystal. Thus, for example, if the angles a and x be cut away, so as to leave parallel surfaces, and the surface at x be placed upon a sheet of paper, with a dot upon it, looking through the corresponding surface at a the dot will appear single. This direction is called the *optic* axis. In every direction *perpendicular* to the optic axis, it is found that the *extraordinary* ray obeys the ordinary laws of single refraction, its index of refraction being the minimum, viz., 1·483.

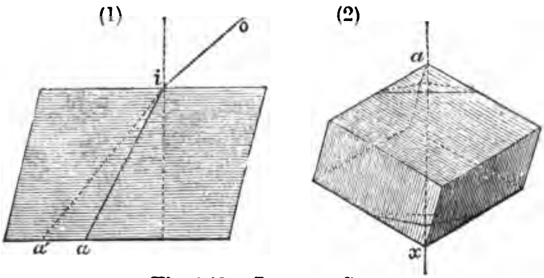


Fig. 142.—Iceland Spar.

Uniaxal crystals are sometimes divided into *positive* and *negative;* in the former, the ordinary refractive index is less, and in the latter, greater than the extraordinary index.

Quartz and ice are examples of the first class; Iceland spar, tourmaline, and emerald of the second class.

(2.) *Biaxal.*—Such crystals have two optic axes, or two directions in which there is no bifurcation. We have examples in the following cases: crystallised sugar, mica, topaz, felspar, and selenite.

The *non-separation* of the ray in either case is explained on the assumption that the molecular grouping is *symmetrical* round the axis or axes, in virtue of which the elasticity of the ether is the same.

CHAPTER IX.

POLARIZATION OF LIGHT.

156. Origin of the term "Polarised."—"Huygens found that when a common luminous beam passes through Iceland spar in any direction save one (that of the optic axis), it is always divided into two beams of *equal* intensity; but that when *either* of these two half-beams is sent through a second piece of spar, it is usually divided into two of *unequal* intensity; and that there are two positions of the spar in which one of the beams vanishes altogether. On turning the spar round this position of absolute disappearance, the missing beam appeared, its companion at the same time becoming dimmer; both of them then passed through a phase of equal intensity; and when the rotation was continued, the beam which was first transmitted disappeared.

"Reflecting on this experiment, Newton came to the conclusion that the divided beam had acquired *sides* by its passage through the Iceland spar, and that its interception and transmission depended on the way in which those sides presented themselves to the molecules of the second crystal. He compared this *two-sidedness* of a beam of light to the *two-endedness* of a magnet, known as its polarity; and a luminous beam exhibiting this two-sidedness was afterwards said to be *polarised*."*

The term "polarised" cannot be said to be a happy one, especially in connection with the undulatory theory; but it has now become established, and, like many other terms in science, should be held to be only the name given to a *certain* phenomenon, without any reference to its exact nature.

157. Effects of Tourmaline.—A good notion may be obtained of the general nature of polarised light by a few

* Tyndall's *Notes*, pp. 60-61.

simple experiments with two thin plates of tourmaline, *cut parallel to the optic axis* of the crystal. This mineral possesses the peculiar property of quenching the ordinary ray, whilst it gives comparatively free passage to the extraordinary one. On placing the two plates, one upon the other, with their axes parallel, it is observed that light readily passes through the two crystals. But on gently rotating one of the crystals, the light becomes fainter and fainter, until they assume a position at right angles to each other, when little or no light passes through. The appearances observed are shown in fig. 143. During a complete revolution of one crystal on the other, the crystals are twice parallel (at 0° and 180°), and twice crossed at right angles (at 90° and 270°), thus giving rise to *two* maxima and *two* minima in the intensity of the transmitted light.

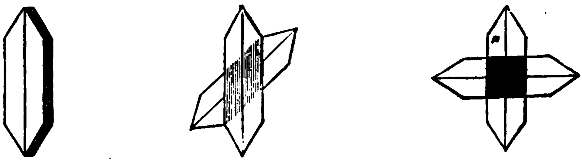


Fig. 143.—Tourmaline Plates.

We naturally deduce from this, that ordinary light, in passing through a crystal of tourmaline, undergoes *some change* in its character, whereby it has no longer the power to pass through another plate of tourmaline equally in *all* positions; in a word, it is *polarised.*

158. Plane Polarization.—The question arises, What is the nature of this change? The *undulatory* theory alone is competent to give a satisfactory answer.

In ordinary light, it is believed that the ether particles vibrate in all directions *across* the line of propagation; in other words, the vibrations take place in every plane in succession, but in no regular manner, perpendicular to the direction of the wave's motion. What occurs when light passes through a tourmaline plate cut parallel to the axis is this: *The vibrations of the emergent beam are reduced to the same plane, and that plane is parallel to the axis, all the others being quenched within the crystal.* The emergent beam is

thus called a beam of *plane polarised light.* In general, therefore, "plane polarization" is that condition which light assumes, when the vibrations of the ether particles are executed *in one and the same plane.*

When light is said to be polarised in a *particular* plane, it is understood that the vibrations of the ether particles take place *at right angles* to that plane.

159. Polariscope.—A *polariscope* consists essentially of two parts: (1), the means by which the light is polarised, called the *polariser;* and (2), the means by which the light thus polarised is examined or analysed, called the *analyser.* There are several varieties of the instrument. One of the simplest consists of two crystals of tourmaline, mounted and fixed in loops (fig. 144), at the end of a wire which forms a spring, thus keeping the two crystals together, and serving also as a handle. Either of the crystals is made to rotate in its mounting, and may be thus brought into any angular position in regard to the other. Both are cut parallel to the axis; either, therefore, may be made the polariser. In any such instrument, the analyser, in respect to ordinary light, is itself a polariser; hence the two parts are reciprocal, or can be made to change places.

Fig. 144. — TOURMALINE PINCETTES.

As a polarising agent, however, tourmaline has the objection of giving colour to the transmitted light. Some white, or nearly white, specimens of the mineral have been found, but they are rare. The most common specimens have a reddish-brown or brownish-green colour.

160. Polarization by Reflexion.—If a beam of light be incident upon almost any reflecting surface (excepting *metals*), it is found after reflexion to give indications more or less of polarization. Thus, for example, if a glass plate be taken into a darkened room, and placed in the track of a beam admitted through a small aperture in the shutter, it is found that the reflected light, as examined by a tourmaline plate, is more or less polarised according to the angle of incidence; in other words, by viewing the reflected beam through the plate whilst the latter is turned round in its own plane, varying degrees of brightness in

the transmitted beam are observed, depending upon the magnitude of the angle of incidence. If the rays be incident at a *particular* angle, it is found that the variation in brightness of the reflected rays manifested in the revolving plate is a *maximum*. That angle is called the *polarising* angle; in general, for any substance, it is that angle of incidence at which the reflected beam is perfectly polarised, or has its vibrations all reduced to a common plane. For glass, this angle is found to be 54° 35′; for water, 52° 45′; for diamond, 68°.

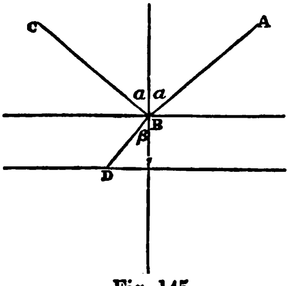


Fig. 145.

Brewster established this interesting law in regard to different substances: *The tangent of the polarising angle of a substance is equal to its index of refraction.*

From this we may easily prove that the *reflected and refracted rays are at right angles to each other*. Take the case of glass. Let AB be the incident ray; α the angle of incidence, or the polarising angle (fig. 145), β the angle of refraction.

$$\text{Then}\quad \tan\alpha=\tfrac{3}{2},\ \text{but}\ \frac{\sin\alpha}{\sin\beta}=\tfrac{3}{2}\ \text{(1st law of refraction)}$$

$$\therefore\ \tan\alpha=\frac{\sin\alpha}{\sin\beta},\ \text{or}$$

$$\frac{\sin\alpha}{\cos\alpha}=\frac{\sin\alpha}{\sin\beta};\ \text{hence}\ \cos\alpha=\sin\beta,\ \text{or}\ \alpha+\beta=90^\circ,$$

$$\therefore\ \text{CBD}=\text{a right angle.}$$

The polarising angle, therefore, *is that angle of incidence for which the reflected ray is perpendicular to the refracted ray*—another way of expressing the above law. We have hence a means of determining the index of refraction of a substance, by finding the polarising angle. The reflexion of the solar rays which occurs on the part of the atmosphere, more especially when the sun is low, has been shown to cause traces of polarization.

161. Glass as an "Analyser."—Let the beam reflected from a glass plate at the polarising angle be received upon

a second plate arranged in a position parallel to the former; the beam reflected from the first plate falls upon the second also at the polarising angle, and is wholly reflected. If now the *second* or *upper* plate be slowly turned round in *such a manner as that the beam reflected from the lower plate still falls upon it at the polarising angle*, the reflexion from the upper plate becomes less and less, until the rotation amounts to 90°, when all reflexion vanishes—the beam is then wholly transmitted. Continuing the revolution of the plate, reflexion sets in again, which gradually increases until the rotation amounts to 180°, when a second time the beam is wholly reflected. Thus during an *entire* revolution of the upper plate there are two positions where the reflexion is complete, and two positions where it altogether vanishes. The upper plate acts, therefore, like the tourmaline, and plays the part of an "analyser."

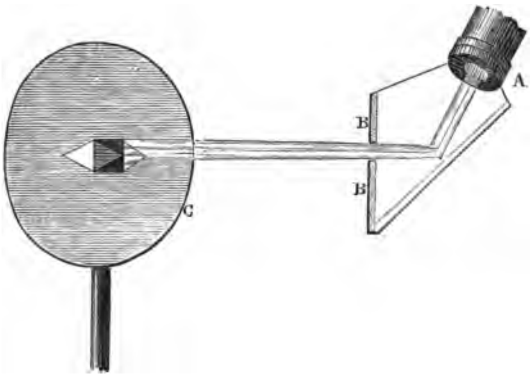


Fig. 146.—Experimental Illustration.

These results lead to the conclusion that the vibrations of the polarised beam are executed *in a plane at right angles to the plane of incidence*, or, which is the same thing, *in a plane parallel to the polarising surface.* It is difficult to believe that it can be otherwise; for in the two positions of *no* reflexion, when the angle of rotation amounts to 90° and 270°, the vibrations of the polarised beam lie *in the plane*

of incidence of the upper plate, a state of matters which seems to render reflexion impossible.

162. Experimental Illustration.—A striking illustration of polarization by reflexion is afforded by the following experiment: A sunbeam passes through a small aperture at the end of a tube A (fig. 146); it falls upon a glass plate (blackened at the back), at the polarising angle, and is reflected through an aperture in the shutter, BB, of a darkened room. The polarised beam then falls upon a screen C, in the middle of which is fixed a square pyramid of smoked glass D, whose sides so converge towards the apex, as that the polarised beam also falls upon them at the polarising angle. On the screen there is presented the appearance indicated in the figure—shadows of the pyramid are cast on the right and left, and none above or below, proving *no* reflexion from the two sides, whilst from the other two sides reflexion has taken place freely. An ordinary beam being admitted, reflexion occurs at the four faces, and no shadows are observed on the screen.

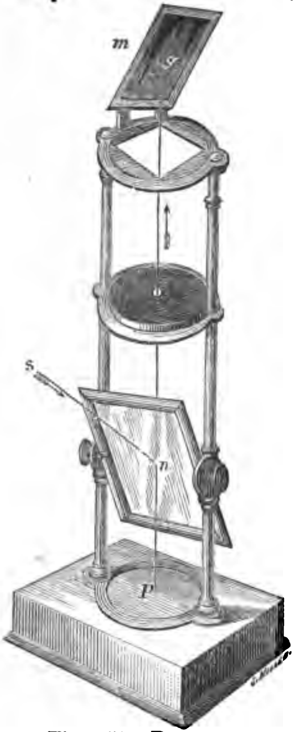


Fig. 147.—Reflecting Polariscope.

163. Reflecting Polariscope.—A very complete instrument of this kind was invented by Norremberg. It is represented in fig. 147. The lower reflector *n* is a transparent glass plate, movable about a horizontal axis, and acts as the "polariser," the upper one *m*, formed of blackened glass, is adjusted to move horizontally and vertically, and acts as the "analyser." At the foot of the uprights is a mirror, *p*, of silvered glass. Its action is similar

to the glass plates in Art. 161. The ray S*n*, falling upon the plate *n* at the polarising angle, is reflected towards the mirror *p*, which sends it in the direction *pg*. The ray thus polarised falls upon the reflector *m*, which is adjusted also at the polarising angle. When the planes of incidence coincide, the ray is reflected from the upper mirror, but when they *cross* each other, as in the figure, all reflexion ceases. The reflectors *n*, *m*, can be adjusted to any angles, and thus the varying amounts of polarization can be so far compared.

164. Polarization by Single Refraction.—When light falls upon a transparent medium, such as glass, there is not only reflexion, but also refraction, part of the incident light entering the glass. Now it is found that whatever quantity of polarised light there is for any incidence *other than the polarising angle* in the reflected beam, there is always the *same* quantity in the refracted beam. At the polarising angle, however, the refracted beam exhibits traces of polarization.

If a beam be incident at any angle upon a bundle of thin glass plates, it is found that the polarization of the transmitted beam increases with the number of plates, until they amount to ten or twelve, when the emergent beam becomes completely polarised, whilst the reflexion diminishes, and eventually ceases altogether. By examining this polarised beam with a tourmaline plate, it can be shown that the vibrations occur in a plane *at right angles* to that in which the vibrations of the reflected polarised beam are executed; in other words, the vibrations occur *in* the plane of the incident beam.

165. Polarization by Double Refraction.—The two beams into which a bi-refractive crystal, such as Iceland spar, divides a beam of light, are both polarised. This may be proved by examining each beam separately with a tourmaline plate; in a certain position of the plate *either beam may be quenched.* It is found, moreover, that the position of the tourmaline, in which the extraordinary beam is quenched, is *at right angles* to that in which the ordinary is quenched. Or if both beams be examined simultaneously by the rotating plate, the position which extinguishes the *ordinary* beam causes the maximum brightness in the *extraordinary*; and

vice versâ. From this it follows that the two beams are polarised *in planes at right angles to each other.* The *direction* in which the vibrations are executed in the ordinary beam is believed to be *perpendicular* to the optic axis; in the other, therefore, the vibrations are *parallel* to the optic axis.

Seeing that ordinary light is thus capable of being broken up into *two polarised beams of equal brightness,* we may regard it as equivalent to two such beams whose vibrations take place at right angles to each other. Thus let R be a beam of common light (fig. 148), whose combined vibrations occur in planes perpendicular to each other; in traversing the spar it is *sifted,* so to speak, and resolved into two separate beams AB, CD, one the ordinary beam, and the other the extraordinary, each of whose vibrations is reduced to one plane, and is therefore polarised.

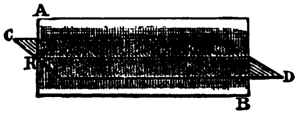


Fig. 148.

166. Nicol's Prism.—Iceland spar, from its transparency and absence of colour, is the most valuable polarising agent we possess. It only becomes necessary to abolish one of the beams, so as to have a *single* beam of intense polarised light. This is effected in the so-called "Nicol's prism." A crystal of the spar is cut across obliquely, the section AB being parallel to the *principal* plane. The two parts thus obtained are well polished and are then cemented together in their natural position by Canada balsam, the index of refraction of which substance is *intermediate* to the indices of the ordinary and extraordinary rays. The action of the prism is this: A ray of common light (R) is separated into the ordinary (O) and extraordinary (E) rays. O encounters a medium having a less refractive power than itself, and falling very obliquely upon it, under-

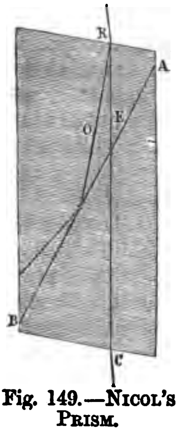


Fig. 149.—Nicol's Prism.

goes total reflexion; whilst E, encountering a medium which has a greater refractive index, penetrates it, and pursues its course till it emerges from the opposite face, as a completely polarised ray. The ordinary ray is, by this artifice, got rid of. A Nicol's prism, or, as it is often called, simply the "Nicol," is admirably adapted as an analyser. Two "Nicols," therefore, placed one in front of the other, give a very perfect form of polariscope.

167. Experimental Illustration.—That the two beams in Iceland spar are polarised in planes at right angles to each other may be strikingly shown by the apparatus represented in fig. 146. Admit the sunbeam *directly* into the darkened room, and interpose a crystal of Iceland spar. If the ordinary beam fall upon the pyramid, the shadows are thrown right and left upon the screen; with the extraordinary beam, the shadows appear above and below.

168. Effects produced by introducing a Plate of Tourmaline or Selenite between two Crossed Tourmalines.—The transition from light to darkness as one tourmaline plate is made to rotate over another, may be easily understood from the principle of the "resolution of forces" in mechanics. Thus when the axes of the crystals are parallel, the vibrations of the ether are coincident, and the light is transmitted through both. Let the second crystal assume the position CD (fig. 150), and let *ab* represent the *amplitude* of the vibrations of the beam passing through the first crystal. Draw perpendiculars on CD from the points *a*, *b*; the vibration *ab* is now resolved into two, *ac*, *cd*, whereof the first, being perpendicular to the axis, is quenched by the second crystal—the other component *cd* is transmitted. In the position EF in like manner, *ef* represents the transmitted part

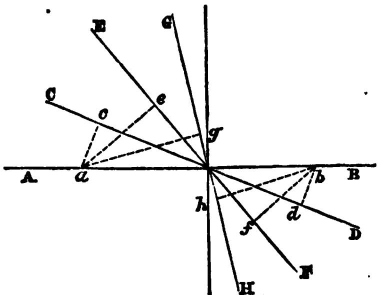


Fig. 150.—Effects of Tourmaline Plates Explained.

of the vibration, and in the position GH, *gh*. Thus the amplitude of the vibration is represented by the *diminishing* lines *cd*, *ef*, *gh*; in other words, the intensity of the transmitted light diminishes as the second crystal approaches the perpendicular position. In the last-mentioned position, the component *along* the axis vanishes, and hence all transmission is arrested.

From this we can understand the effect produced by introducing a third tourmaline plate between the crossed tourmalines. Should the axis of the third plate be parallel to, or coincident with, *either* of the other two, the common area should still be *dark*. But if the axis of the introduced plate be *oblique* to both, the light traversing the first plate in encountering the second would have its vibration *changed*. The emerged light from the second meets the third, therefore, obliquely, and hence part of the light would be transmitted, and the darkness is so far obliterated. This reasoning on theoretical grounds is completely carried out by actual experiment.

Introducing a thin plate of gypsum, otherwise called selenite (crystallised sulphate of lime), cut in the direction of the plane of best cleavage, we find similar effects. This mineral, as we have seen, is bi-refractive. Like Iceland spar, it breaks up a beam of light into two beams, which are polarised at right angles to each other. There are two positions, in which if the selenite be placed, it is incompetent to abolish the darkness of the common area of the crossed tourmalines. The reason is, that in both the vibrations of the light after it has traversed the selenite are parallel to the axes of the tourmalines. In any other position light passes through.

CHAPTER X.

INTERFERENCE OF POLARISED LIGHT—CHROMATIC EFFECTS—CIRCULAR AND ELLIPTICAL POLARIZATION.

169. Interference of Polarised Light.—We have seen the circumstances under which two rays of ordinary light meeting each other may produce interference (Art. 148). We are now to notice the conditions under which polarised light may produce the same effect.

The extensive and searching experiments of Arago and Fresnel on this subject led them to the following general results:—

"(1.) When two rays, polarised in the *same* plane, interfere with each other, they produce by their interference *fringes of the very same kind* as if they were common light.

"(2.) When two rays of light are polarised *at right angles* to each other, they produce *no* coloured fringes in the same circumstances under which two rays of common light would produce them. When the rays are polarised in planes inclined to each other at any other angles, they produce fringes of intermediate brightness, and if the angle is made to change, the fringes gradually decrease in brightness from 0° to 90°, and are totally obliterated at the latter angle.

"(3.) Two rays polarised at right angles to each other, and afterwards brought into the *same* plane of polarization, produce fringes by their interference like rays of common light, *provided they originated in a pencil, the whole of which was originally polarised in any one plane.*"*

170. Chromatic effects with Bi-refractive Crystals.—A number of interesting phenomena, dependent upon the interference of polarised light, are obtained with bi-refractive crystals. These are well studied by taking two Nicols, the

* Ganot's *Physics*, p. 549.

one acting as polariser, and the other as analyser, and introducing between them a plate of selenite.

Let us first consider the conditions necessary for interference. Suppose AB, CD (fig. 151), to represent the directions of vibration of the divided beam emergent from the selenite, *oblique* to the direction EF, representing that in which the vibration of the beam passing through the polariser takes place. Let *ab* be the *amplitude* of the vibration of the polarised beam; draw the perpendiculars as in the figure.

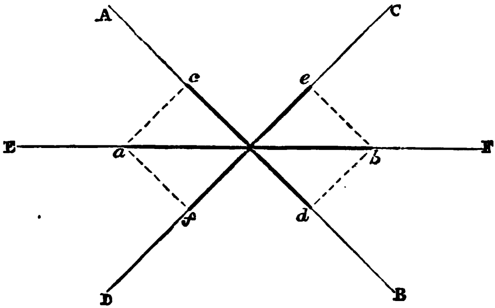


Fig. 151.

The vibration *ab* is resolved into the two *cd*, *ef;* these represent, therefore, the *amplitudes* of vibration of the divided beam.

Now, in consequence of a difference of elasticity in the crystal, the waves of ether are more retarded in the one direction than in the other, or which is the same thing, though the *rate* of vibration remains the same, the waves are more shortened in the one direction than in the other. Whatever be the difference of retardation, however, it is clear that so long as the vibrations are executed *at right angles* to each other, *no* interference can take place. But should these vibrations be reduced to a *common* plane, then owing to the difference of retardation, interference is rendered possible. This is the function of the analyser—it reduces the rectangular vibrations of the selenite to a single plane. If the thickness of the plate be such as to cause the one set of

waves to meet the other in the *same* phase, the two sets of waves conspire in action; on the other hand, if the thickness be such as to cause them to encounter each other in *opposite* phase, the two systems oppose each other, and interference sets in.

Suppose, then, a beam of solar light to be admitted through an aperture in the shutter of a darkened room. Two Nicols, suitably mounted on stands, are placed in its path, and a screen is adjusted at some distance directly opposite. Let the Nicols be crossed, then the screen is dark. If a thin plate of selenite of uniform thickness be introduced between them, with either of its planes of vibration coincident with the polariser, no light passes through (as in the case of the tourmaline plates)—the screen still remains dark. If introduced obliquely, *coloured* light is observed on the screen. Whence the colour? It arises from the fact that the thickness of the plate is such as to arrest by interference one of the constituents of the solar light, the remaining constituents reaching the screen. For example, if the plate be such as to arrest the red rays, then the light on the screen is the *complementary* colour, or that resulting from the blending of the residuary rays. Thus, by taking plates of different thickness, in accordance with the *difference of wave-length* of the individual colours, we can imagine how any one of these may be arrested, and the screen therefore tinged with different hues. The maximum intensity of coloured light is obtained when the planes of vibration of the plate make an angle of 45° with those of the polariser and analyser.

171. Action of a Selenite Disc of variable Thickness.—Some beautiful effects are obtained with a disc of selenite, made thin in the centre, and gradually increasing in thickness outwards.

If the aperture be closed with a piece of red glass, and the disc be introduced between the crossed Nicols, there is presented on the screen a series of concentric rings, alternately red and dark. The red rings result from thicknesses in the disc where *coalescence* in the vibrations occurs, and the dark rings from thicknesses where *interference* occurs. With blue glass, alternate blue and dark rings are obtained, but of smaller diameter. Hence when *white* light is used, or the

aperture is left free, we have thrown upon the screen a series of iris-coloured rings. With monochromatic light, if, whilst the polariser and disc are kept stationary, the analyser be turned round 90°, that is when the planes of vibration of the Nicols are parallel, the bright and dark rings change places. Thus if a ring, at any distance from the centre, be bright when the Nicols are crossed, the same ring is dark when they are parallel. With white light, the tints of the rings are complementary.

Similar phenomena to those exhibited with selenite are obtained with all double-refracting crystals, with unannealed glass, and with annealed glass unequally heated or mechanically strained.

172. Rings surrounding the Optic Axes of Uniaxal and Biaxal Crystals.—If a *conical* beam be sent through a plate of an uniaxal crystal, such as Iceland spar, cut perpendicularly to its optic axis, the central ray alone passing along this line escapes double refraction—all the others are divided, and vibrate in planes at right angles to each other, each of the rays being more retarded than its companion.

Introducing, therefore, the plate between the crossed Nicols, under such circumstances the polariser reduces the divided rays into such a state as to cause interference, as in the case of a selenite plate. If the conical beam consist of monochromatic light, there is presented on the screen a series of alternate bright and dark rings surrounding the bright centre, but in addition a *black cross* is obtained (fig. 152). The arms of the cross coincide with the *axes* of the Nicols, and result from the light being *wholly* intercepted in these directions. If the Nicols be turned round 90°, the bright and dark rings change places as before, and the cross is changed to a bright one, as in fig. 153. With white light a series of beautiful iris-coloured rings are obtained; when the axes of the Nicols are perpendicular, with a black cross, and when parallel, with a white cross. In the latter case, the tints of the rings are complementary to those deduced in the former case.

With a plate of a biaxal crystal, such as topaz, the appearance represented in fig. 154 is obtained, when the Nicols are crossed. The points A, B, are the optic axes, and round these

Fig. 152

Fig. 153

Fig. 154

as centres the coloured bands are formed. The curve is known among mathematicians as the "Lemniscata," and is proved mathematically to be just that which would be assumed in accordance with the undulatory theory.

173. Circular and Elliptical Polarization.—Light is said to be (1) *circularly polarised* when the vibrations of the ether particles are executed in circles; and (2) *elliptically polarised* when they are performed in ellipses.

To understand how this is possible, let us consider the behaviour of a pendulum when influenced by two motions at right angles to each other. Suppose the original plane of the motion (fig. 155) to be in the direction AB, and that when the pendulum is at the limit of its range A, a shock is imparted to it in the direction A*a*, which of itself would be sufficient to carry it from O to C, were it at rest; then the combined motions will evidently cause it to move in the circle ACBD, the time of describing which will be exactly equal to that in which it would describe the course AB or CD, were either motion to act separately upon it.

Again, if the shock imparted to it at A be *less* or *greater* than what is sufficient to carry it from O to C were it at rest, the pendulum will describe an ellipse; in the former case AB being the *major* axis of the ellipse, and in the latter case the *minor* axis.

Assuming a *complete* vibration of the pendulum to be an excursion to *and* fro, that is, from A to B and back again, it will be seen that a *circular* path will be described by the pendulum when the shock *succeeds* the primitive motion by a *period of time equal to that of a quarter of a vibration*. The same is true should the shock *precede* it by the same period. If the shock be imparted whilst the pendulum is passing the lowest point of its range O, it will move in an intermediate direction between AB and DC, but will keep the *same* plane.

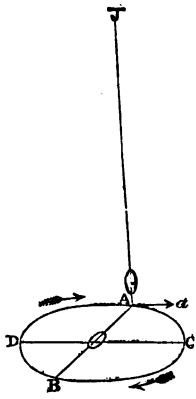


Fig. 155.

Applying this to light, we see that if the ether particles

are urged in two directions, at right angles to each other, with the same force; and *if the one motion either succeeds or precedes the other by a quarter of a vibration or undulation*, then the beam would be circularly polarised. If the one motion succeeds the other by *half* an undulation, the vibrations occur in planes. In any other case the vibrations are elliptical.

174. Fresnel's Rhomb.—It appears, therefore, that were we able to decompose a beam of plane polarised light into two beams of *equal* intensity, polarised at right angles to each other, and differing in their path by a quarter of a wave-length, we should obtain a beam of *circularly* polarised light. This was effected in an ingenious way by Fresnel. He constructed a rhomb of glass, ABDC (fig. 156), with an acute angle A about 54°. Allowing a beam PQ, polarised in a plane making an angle of 45° with the section ABCD, to fall perpendicularly on the face AB, he found it split up by the two reflexions at Q and R into two beams of equal intensity, polarised at right angles to each other, but the one retarded, in reference to the other, a quarter of a wave-length.

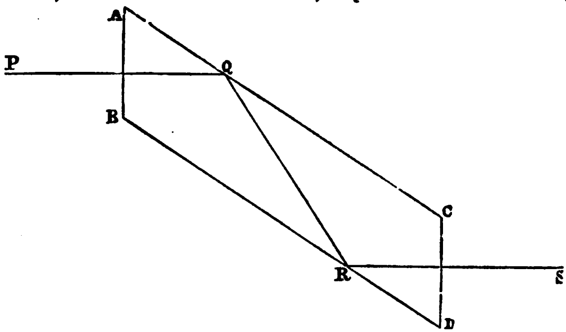


Fig. 156.—FRESNEL'S RHOMB.

The beam emergent from the rhomb was therefore circularly polarised. This is one of the best means of obtaining circularly polarised light, and is applicable either to homogeneous or compound light, provided the incident light has been previously plane-polarised.

On examining the emergent beam from the rhomb with

tourmaline, as the plate is turned in its own plane, no variation of brightness is observable, indicating therefore a change of condition in the *original* beam PQ, which itself disappears at each quarter of a revolution of the plate. If the circularly polarised beam be made to pass through a second rhomb, similarly situated to the first, it is found to be reconverted into a plane polarised beam. This is just what we would expect; for, referring again to the pendulum, the two beams on emergence from the second rhomb now differ in path by *a half* wave-length, they are incompetent therefore to produce, by their combined effect, any other but a motion in a *single* plane. The plane of polarization, however, is inclined at an angle of 45° to the primitive plane of polarization.

It appears, therefore, that we may regard a beam of plane polarised light as equivalent to two half-beams of equal intensity circularly polarised in *opposite* directions.

175. **Elliptical Polarization.**—It appears from theoretical considerations, as well as from experiment, "that when a ray of light, polarised in any plane, undergoes reflexion in a different plane, the reflected portion comes off in all cases more or less *elliptically* polarised; that is to say, it consists of, or can be resolved into, two rays, the one polarised in the plane of incidence, the other in a plane at right angles to it; that both these portions have undergone a change of phase at the moment of reflexion, but *not the same for both*, so that arriving at the surface in the same phase, they quit it in different phase, and therefore constitute by their superposition an elliptically polarised ray.

"The amount of ellipticity varies for each reflecting medium, according to the nature of its material, with the angle of incidence at which the reflexion takes place, and also with the inclination of the plane of incidence to that of the primitive polarization of the incident ray. If the reflexion take place on ordinary transparent media of not very high refractive power, as glass or water, and at the polarising angle, the degree of ellipticity is so slight that the vibration may be considered as rectilinear, and the reflected ray as completely polarised in the plane of incidence. As the refractive power of the substance increases, the ellipticity impressed is greater, and in some substances, of very high

refractive power, such as diamond, . . . it is considerable. From such bodies, accordingly, it is not possible at any angle of incidence to obtain a reflected ray completely polarised in one plane. And when we come to reflexion from polished metals, the ellipticity becomes very considerable."*

In Fresnel's rhomb (fig. 156), the divided ray QR is elliptically polarised, the difference of phase of the component rays being $\frac{1}{8}$ of a wave-length. By the second reflexion at R, this difference is increased by another $\frac{1}{8}$ of a wave-length; hence the difference of phase on emergence amounts to $\frac{1}{4}$ of a wave-length, and the emergent ray becomes in consequence circularly polarised.

Airy has shown that when a ray of plane polarised light is made to pass through a plate of *quartz* (rock crystal), cut perpendicularly to its optic axis, the direction of transmission being *inclined to the axis*, the ray is divided into two elliptically polarised rays, whose vibrations are executed in *opposite* directions.

From what has been stated, it is clear that we may consider both plane and circular polarization as only *particular* cases of elliptical polarization.

176. Rotatory Polarization.—Quartz and a few other bodies possess the remarkable power of *twisting* the plane of vibration of a polarised ray. Thus, if a plate of quartz, cut perpendicularly to the optic axis, be introduced between the crossed Nicols, and monochromatic light (say red), be used, a red band of light is seen upon the screen. By turning round the analyser over an angle corresponding to the angle of rotation through which the plane of vibration has been twisted, the band disappears. Each colour is found to be twisted, *with the same thickness of plate*, through a particular angle; hence to cause extinction, it is necessary to rotate the analyser through the corresponding angle.

When *white* light, therefore, is used, there are presented on the screen the different colours of the spectrum in succession.

Some specimens of quartz, however, require the analyser to be twisted in the *opposite* direction to obtain the *same* order in the colours. Those which twist the plane of vibration to the *right*, that is, in the direction of the hands of a

* Herschel's *Popular Scientific Lectures*, pp. 377-378.

watch are distinguished as *right-handed* crystals, in the opposite direction as *left-handed.*

Biot was the first to investigate, with success, this curious subject. He deduced the two following chief laws:—

(1.) The rotation of the plane of polarization is proportional to the *thickness* of the plate.

(2.) The rotation is different for the different rays, and *increases* with their refrangibility.

Certain liquids also have been found to possess this property. Thus a solution of sugar in water, oil of lemons, a solution of camphor in alcohol, twist the plane of polarization to the *right;* whilst oil of turpentine, and an aqueous solution of gum-arabic, twist it to the *left.* It is found that such substances do not lose their rotatory power, even by mixture with liquids which are destitute of the property. They are all, however, much feebler in this respect than quartz, hence a considerable *depth* of fluid is requisite to produce any marked effect.

177. Explanation of Rotatory Polarization.—The above phenomena derive their explanation from the principle of circular polarization.

Fresnel has proved, beyond doubt, that when a plane polarised beam passes through a plate of quartz, cut as before mentioned, it is resolved into two beams circularly polarised, moving in opposite directions, but with *unequal* velocities. Let AB (fig. 157) be the plane of polarization of the incident beam. In the first place, suppose in traversing the quartz it is decomposed into two beams, moving with the *same* velocity in opposite directions, then the superposition of these two beams will give rise to a single emergent beam, whose plane of polarization will still coincide with the primitive plane of polarization AB, for any particle of ether at A is urged in opposite directions by two equal forces Aa, Aa'. If, however, as Fresnel has shown, the separate beams traverse the quartz with different velocities, then on emergence—the one beam being in advance of the other—the two beams will form one, whose plane of

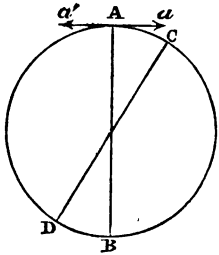


Fig. 157.

polarization can no longer be in the direction AB, but in some new direction CD. The thicker the plate the more retarded is the one beam in reference to the other, and therefore the greater the angle of rotation of the emergent beam.

The varying amounts of rotation for the successive colours, with the same thickness of plate, can be readily imagined, therefore, to be due to an *increasing* difference between the velocities of the divided beams.

In the figure, the plane of polarization is represented as twisted to the *right*. In this case we can understand that the velocity of the first beam is *greater* than that of the second. If the rotation take place to the left, then the velocity of the first is less than that of the second. In other words, in the former case the first beam is in *advance* of the second by a certain interval; in the latter it is in *arrear;* hence the difference between right-handed and left-handed crystals.

178. **Magnetization of Light.**—The plane of polarization may be caused to rotate, in certain circumstances, under the influence of magnetism. This was Faraday's discovery. A rectangular bar of "heavy glass" (silico-borate of lead) is placed over the poles of an electro-magnet in the shape of a horse-shoe. A solar beam, or a beam from an electric lamp, is polarised by a Nicol, and made to traverse the glass, the emergent beam is then received upon a *crossed* Nicol, placed at the other end of the bar. So long as the horse-shoe remains unexcited, no light reaches the screen. But on establishing the electric current, light instantly flashes out upon the screen. Faraday explained the result by the *direct* action of the magnetism thus excited upon the light traversing the glass—a fact which he called the "magnetization of light." It it now more generally believed to be due to the action of magnetism upon the glass itself, whereby its particles undergo strain, or its molecular arrangement is affected.

It has been found that all transparent solids and liquids manifest a similar effect in a more or less marked degree.

The amount of rotation increases with the strength of the current; whilst the *direction* in some substances is the same as that in which the current circulates, and in others the reverse.

HEAT.

CHAPTER I.

THEORIES OF HEAT—EXPANSION OF SOLIDS.

179. Nature of Heat.—Two theories have been proposed in reference to the nature of *heat.* One of these is called the *material* theory, the other the *mechanical* or *dynamical* theory.

According to the material theory, heat is a *species* of matter—it consists of an imponderable substance surrounding the molecules of bodies, and in virtue of its attraction for other matter, and its repulsion for its own particles, it can readily pass from one body to another. According to the mechanical or dynamical theory, heat is an *affection* or *condition* of matter—it is due to a vibratory motion among the particles of a body. Each particle or molecule is believed to have a motion either backward or forward, or round and round, the molecules being so small, however, and the motion so rapid, that the eye is unable to perceive what really takes place. Further, the molecules of warm bodies are capable of communicating a vibratory motion to the surrounding *ether*, in virtue of which contiguous bodies become heated. Very hot bodies are, on this hypothesis, those whose particles have a rapid vibratory motion amongst themselves, and which thereby greatly excite the all-pervading ether.

The latter theory is the one almost universally held by modern physicists, and is adapted, as we shall afterwards see, to give a satisfactory explanation of the different phenomena.

180. Elementary Facts relating to Heat.—We become conscious of the presence of heat in a body, either by means

of the sense of touch, or by various invisible phenomena accompanying its production or transference from one body to another.

On applying the hand to various objects, *touch* enables us to distinguish bodies which impart heat to the hand from those that abstract heat from it; the former bodies we call warm, or hot, and the latter cool, or cold. The same sense, in a more refined manner, renders us conscious of the proximity of bodies hotter than ourselves, even where there is no actual contact between them and the skin. The vibrations set up in the ether by the hot bodies are rendered sensible by the skin, and thereby reconverted into heat, and thus the same nerves are stimulated that are affected when a hot body touches the skin.

Bodies made sufficiently hot become incandescent, that is to say, they shine with a light of their own, and are visible in the dark. Here the eye renders us conscious of the presence of heat, for very early in life we learn to associate the luminosity of a body with the presence of heat.

Bodies on being made hotter or colder undergo certain physical changes, some of which, such as the melting of wax or the boiling of water, are visible to the eye. The others can be rendered evident by instrumental aid. The following are the more important of these physical changes:—

(1.) *Expansion and Contraction.*—Bodies (with very few exceptions) expand on receiving an increment of heat, and contract on losing heat. Different bodies expand differently for the same amount of heat. The expansibility of liquids is greater than that of solids, while that of gases is much greater than in the case of solids or liquids.

(2.) *Change of Physical State.*—Solids when sufficiently heated become liquids and liquids vapours; conversely, vapours, when sufficiently cooled, become liquids, and liquids solids.

181. **Expansion by Heat.**—The expansion which a body undergoes in *length* is called its *linear* expansion; and in *volume* its *cubical* expansion.

To illustrate linear expansion, the following apparatus has been devised (fig. 158):—

A metallic bar is supported on pillars, as in the figure.

Its free end presses upon a lever, which in turn acts upon an index, playing over a graduated arc. By this arrangement a multiplying effect is produced upon the index, in consequence of which the smallest elongation on the part of the bar is rendered manifest..

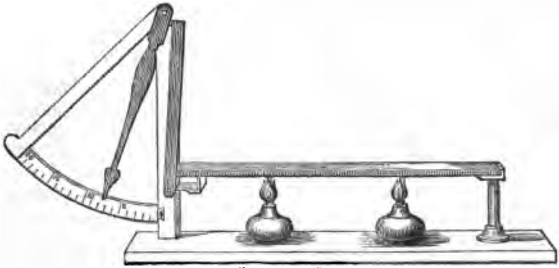


Fig. 158.—LINEAR EXPANSION.

The cubical expansion of a body is shown very simply thus:—A small brass ball (fig. 159) just passes through an aperture in a metal plate supported on three legs. When

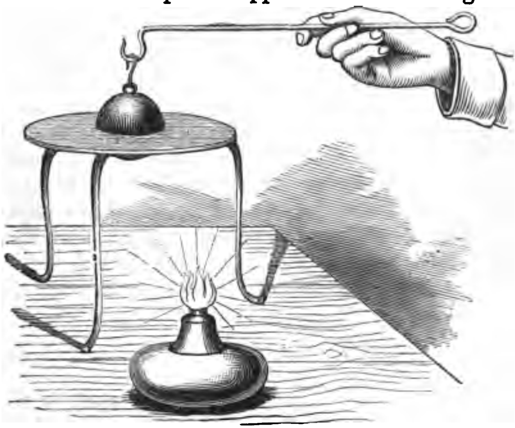


Fig. 159.—CUBICAL EXPANSION.

the ball is heated by being held over a spirit lamp, it refuses to go through the aperture, and will not do so until it regains its former temperature.

182. The Co-efficient of Expansion.—The *co-efficient* of expansion (linear, for instance), may be defined to be that *fraction of a body's length which it expands on being heated* 1° *centigrade*. The co-efficients of many substances have been carefully determined by experiment. The following table may be given as a specimen:—

CO-EFFICIENTS OF EXPANSION (LINEAR).

Zinc	·0000294	Steel	·0000124
Silver	·0000190	Iron	·0000118
Brass	·0000188	Platinum	·0000088
Gold	·0000146	Glass	·0000080

From this table it appears that zinc is the most expansible metal, and platinum the least; also that the expansibility of platinum and glass is nearly the same—hence the reason why a chemist can fuse a platinum wire into a glass tube without liability to fracture.

The co-efficient of cubical expansion is approximately *treble* the linear expansion. This may be proved as follows:—

Imagine a cube of some homogeneous substance to be taken, whose side is unity at a certain temperature; let it be equally heated, and have its temperature raised *one* degree, the edge being lengthened a quantity l, suppose. Then the length of the edge will now be $1 + l$, and the solidity $(1 + l)^3 = 1 + 3l + 3l^2 + l^3$; but since the quantity l is a very small fraction, its square l^2 and cube l^3 will be so inappreciably small that $3l^2 + l^3$ may be left out of the above expression, without sensibly affecting the value. It is reduced, therefore, to $1 + 3l$; whilst then the increase in length is l, the increase in volume is $3l$, or three times the increase in length.

Problems on Expansion—

EXAMPLE I.—A brass rod is 10 ft. long at 0°C; find its length when heated to the temperature of 100°C.

One foot, according to the table, is increased ·0000188 ft. for *one* degree, hence 10 ft. when heated 100° are increased $·0000188 \times 10 \times 100 = ·0188$, and the whole length now equals 10·0188 ft.

EXAMPLE II.—Find the length of a rod of brass which would expand equally with a rod of steel 3 ft. long, under a change of temperature of 10°C.

Let x be the length required, then by the question we have the equation

$$x + x \times \cdot0000188 \times 10 = 3 + 3 \times \cdot0000124 \times 10.$$

Multiplying by 1,000,000, we get

$$1000188\,x = 3000372, \text{ whence } x = 2\cdot9998 \text{ ft.}$$

EXAMPLE III.—The rails from London to Manchester are 188 miles long. Suppose these rails to form one continuous piece at a temperature of 0°C.; what will their lengths be at 20°C., the coefficient of expansion of iron being ·0000118? (May Examination 1872.)

$$\text{The length required} = 188 + 188 \times \cdot0000118 \times 20$$
$$= 188\,(1 + \cdot000236) = 188\cdot044368 \text{ miles.}$$

183. Irresistible force of Expansion or Contraction.—The force with which a solid expands or contracts by the addition or abstraction of heat is almost irresistible. Fig. 160 exhibits an apparatus by which the force of contraction is well illustrated. It consists of a strong iron frame. A and B are two uprights, having sockets for the reception of an iron

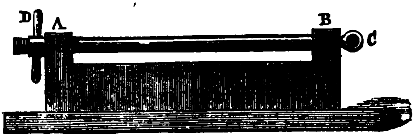


Fig. 160.—FRACTURE BY CONTRACTION.

bar. At the end C there is an aperture through which a small rod of cast-iron slides, and at the other end a bolt D working in a screw. The bar is first heated to redness, and placed as in the figure; the small cast-iron rod is then introduced into the aperture, the bolt screwed up tightly against the support A, thereby bringing the extremities of the rod hard up upon the edged mountings of the support B. In a few minutes the bar falls in temperature, and contracts sufficiently to break the little cylinder. The fracture is accompanied with considerable noise, and very generally the iron bar starts out of its sockets altogether.

184. Practical Applications.—The principle of expansion or contraction is utilised much in practice. The hoop of iron by which a wheel is surrounded is made of the same diameter as the wheel. It is then heated, and in this state is put on the wheel. The whole being thrown into water, the iron hoop contracts with great force, and thus binds the spokes and rim firmly together. A similar method is em-

ployed for binding together the staves of tubs, vats, barrels, etc. The walls of a building have been restored to their perpendicular position by taking advantage of the enormous contractile force of iron.

In the combination of metallic pipes, by which water is brought from great distances for the supply of towns, means must be provided for allowing expansion or contraction to take place freely. Hence the pipes are so constructed as to be capable of sliding one within the other, after the manner of the joints of a telescope. In iron bridges, similar precautions are necessary; they are generally supported on friction rollers.

The same principle explains certain familiar facts. Thus, when hot water is poured into a cold glass vessel, fracture often takes place. This arises from the *unequal* expansion of the glass, the heat not having had sufficient time to extend its influence equally to other parts of the vessel. The same accident may take place when cold water is poured into a warm glass vessel. When the stopper of a decanter becomes firmly fixed, it is not unusual to wrap a cloth steeped in hot water round the neck, the neck thereby expands, and the stopper is freed from its hold.

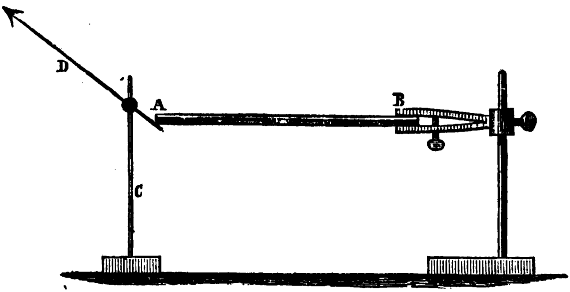


Fig. 161.—Unequal Expansion of Brass and Iron.

185. Illustration of Unequal Expansibility.—The unequal expansibility of brass and iron may be strikingly shown by the following experiment:—AB (fig. 161) is a compound strip of brass and iron (brass uppermost), firmly riveted together, and adjusted as in the figure. The end A rests on the end of a lever, movable about an axis on the support C. On applying

heat to it, the iron being first affected expands, and bends the end A *upwards*. The consequence is that the index falls. But in a short time the heat passes to the brass, and this being more expansible than the iron, the end A becomes bent *downwards*, and thus the index is moved up.

186. Breguet's Metallic Thermometer.—On the same principle is founded Breguet's metallic thermometer, represented in fig. 162. Three strips of silver, gold, and platinum are rolled into a very thin metallic ribbon. This ribbon is coiled into a spiral form, and adjusted as in the figure, the internal face being the silver and the external the platinum. As the temperature rises, the spiral unwinds itself; as it falls, it moves in the opposite direction, and these changes affect the index which plays over the graduated circle.

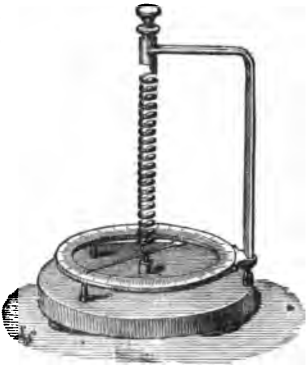


Fig. 162.—METALLIC THERMOMETER.

The introduction of the gold is necessary, as preventing the liability to fracture—the expansibility of gold being intermediate to that of the silver and the platinum.

187. Compensation Pendulums.—In the finer kinds of clocks the variation of temperature is guarded against by the use of what is called a *compensation* pendulum. A common form is the "gridiron" pendulum, represented in fig. 163. It consists of a combination of steel and brass rods, S, B, arranged alternately, and of such length as that the expansion or contraction of the steel rods may be exactly neutralised by the expansion or contraction of the brass ones. To the middle steel rod is attached the bob C. To illustrate its action, let O be the centre of oscillation of the pendulum, or, which is the same thing, let AO be the length of the equivalent *simple* pendulum. In summer the steel rods will expand, and thus tend to lower the point O, or lengthen the pendulum; but the brass rods also expand, and, by their so doing, they tend to raise the point O, or shorten the pendulum.

Fig. 163.—GRID-IRON PENDULUM.

If, therefore, the point O is as much raised by the expansion of the brass rods as it is depressed by the expansion of the steel ones, it will be kept in the same position; in other words, the length AO will be unchanged. In winter, in like manner, if the effects of contraction in the one case be equal to the effects of contraction in the other, the length of the pendulum will be preserved. Hence, by this arrangement, the pendulum is kept constant in its length.

Another form is the "mercurial pendulum" (fig. 164). It consists of a steel rod, widened out at its lower extremity into a frame capable of holding a cylindrical glass vessel filled to a certain level with mercury, hence the name. Its action is as follows:—On an increase of temperature the rod expands, which would thus lower the centre of oscillation O; the mercury also expands, but in an upward direction, thereby raising the centre of oscillation. If, therefore, as before, that point is as much raised by the expansion of the mercury as it is depressed by the expansion of the rod, it will be kept in the same position; in other words, the *length* of the pendulum will be kept unaltered. The opposite effect takes place with a decrease of temperature.

Fig. 164

The important matter in a pendulum of this description is the proper quantity of mercury to be put into the cup. This is usually effected by experiment. If, for example, it should be found, when the temperature rises, that the clock goes too slow, it indicates that the centre of oscillation is more *depressed* by the expansion of the steel rod than it is raised by the expansion of the mercury. There is, therefore, too little compensatory power; in other words, *more* mercury must be put in, and thus by a series of trials just that quantity is obtained which exactly neutralises the changes of length which the rod may undergo.

188. Compensation Balance-Wheel.—The principle of compensation is also applied in the finer kinds of watches, and also in chronometers. A common form is represented in fig. 165. The rim is a compound strip of brass and steel (brass outermost), and consists of two half circles attached to the ends of the spoke of the wheel, the points of separation A and B of the rim being thus at opposite ends and sides of the spoke. On the half circles are disposed several small brass screws for the purpose of *timing* the wheel. When the temperature rises, the steel spoke expands; the half-rims thus recede from the axis, but these become more *curved* than before, and in consequence the small weights are made to approach the axis. If, therefore, the *centre of oscillation* of the wheel is as much moved in by the increased curvature of the rim as it is moved out by the expansion of the spoke, it is clear that it will be kept at the same distance from the axis, and the elasticity of the hair-spring will have the *same* amount of resistance to overcome. When the temperature falls, the *curvature* of the half rims is lessened, and the opposite effects ensue.

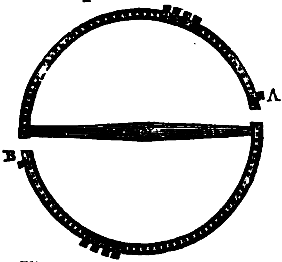


Fig. 165.—COMPENSATION BALANCE-WHEEL.

189. Exceptions to Expansion.—There are some *exceptions* to the principle of expansion by heat which are worthy of notice.

The iodide of silver is found to contract with a rise of temperature.

But perhaps the most singular exception is found in the case of india-rubber. A piece of stretched india-rubber, on being heated, contracts. This substance also forms an exception to the all but general rule, that when a body is stretched, *cold* is developed. If a wire, for example, be lengthened, its temperature is lowered; not so with india-rubber, a stretched piece of rubber is found to have its temperature *raised*.

CHAPTER II.

EXPANSION OF LIQUIDS—THERMOMETRY.

190. Illustration of Expansion of Liquids.—The expansion of a liquid, such as water, may be proved by the following experiment: Take a narrow tube (fig. 166) with a large bulb at its extremity, fill the bulb and part of the tube with coloured water. If now the bulb be heated by a lamp, the water begins to expand, and, owing to the great difference of capacity between the bulb and the tube, any small expansion is rendered manifest by a considerable rise of the liquid in the tube; and in a short time it will reach the top.

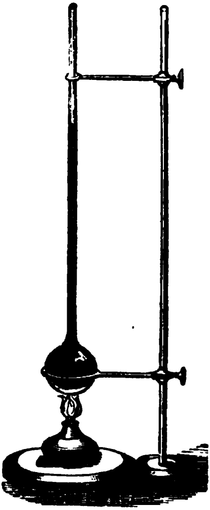


Fig. 166.—Expansion of a Liquid.

The *co-efficient* of expansion of a liquid (having reference, of course, to *cubical* dilatation) is, as before, that fraction of its volume which it expands on being heated 1° C. Of all liquids which have been subjected to experimental investigation, there are none which have been more thoroughly examined than water, alcohol, and mercury.

The expansion of liquids, however, is not perfectly uniform; there is found to be great irregularity near their boiling points. In the case of mercury, its expansion is nearly uniform between the limits of $-36°$ C. and 100° C.

The following co-efficients have been determined in regard to the liquids specified:—

CO-EFFICIENTS OF EXPANSION BETWEEN 0° AND 100° C.*

Alcohol	·00116
Water	·000466
Mercury	·000154
Nitric acid	·0011
Ether	·0007
Sulphuric acid	·0006

191. The Thermometer.—The sensation of warmth or chill which we experience in touching a body can give us no reliable knowledge as to its temperature. Indeed, these sensations may quite mislead us. Thus, for example, if three saucers be filled with cold, lukewarm, and hot water, respectively, and the hands be placed in the first and third saucers for a few seconds, and then plunged together into the middle one, the water there will feel cold to the hand previously immersed in the hot water, while to the other hand it will appear warm. Here we have the same body giving rise to different sensations. We require, therefore, some independent means of determining the temperature of a body, and this is supplied to us by the *thermometer*.

The liquid more generally used in the thermometer is *mercury*, because of its nearly uniform expansibility under a considerable range of temperature. As mercury freezes about $-40°$ C., it ceases to be applicable for very low temperatures. When such are investigated, coloured *alcohol* is used, as it is found to resist congelation under the greatest known cold.

192. Construction of the Mercurial Thermometer.—The essentials of a good thermometer are pure mercury and a capillary tube of *uniform* bore. To obtain the former, ordinary mercury is strained through chamois leather; and in regard to the latter, the uniformity may be tested by introducing a small quantity of mercury and moving it along the tube from end to end by air forced from behind, out of a small hollow india-rubber ball attached to one extremity. If the column is observed to occupy the *same* space throughout, the bore will of course be of the same diameter. This process is called the *calibration* of the tube.

* The above table gives what is known as "the apparent expansion" of the different liquids. The *absolute* or real expansion is obtained by adding in each case the expansion of the glass.

The other end of the tube is now melted and blown into a cylindrical or spherical bulb by means of the india-rubber ball. To fill the instrument, the ball is detached, and the open end melted and formed into a cup-like shape (fig. 167). A small quantity of mercury being introduced into the cup—the bulb is heated by a spirit lamp—the air inside therefore expands, and a portion of it escapes through the mercury. On removing the lamp, the air cools down and contracts, and the mercury is driven into the bulb by the excess of the atmospheric pressure. Another portion of mercury is put into the cup, and the lamp is again applied, another portion of air is expelled, and on the lamp being withdrawn, this new quantity of mercury is forced in. The same operation is repeated until it is thought sufficient mercury has been introduced into the bulb and stem. The small cup being removed, the mercury is then heated till it is made to boil and reach the top. On this taking place, a blow-pipe flame is directed upon the end—the glass is thereby melted, and the top of the tube closed or "hermetically sealed," as it is called. The mercury then shrinks, and settles at a particular level depending upon the temperature of the external air at the time. The quantity of mercury introduced into the instrument must be such as neither wholly to pass into the bulb nor reach the top of the tube when exposed to the ordinary extremes of cold and heat. The instrument is now ready for *graduation*.

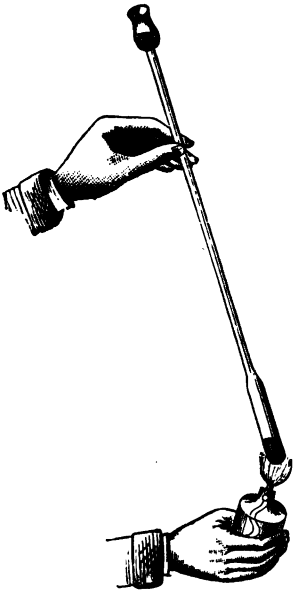


Fig. 167.—Method of Filling Thermometer.

193. Graduation of the Thermometer.—This is effected by selecting two definite temperatures, viz., the temperature

of melting ice and that of boiling water, at the sea level, and under the mean pressure of the atmosphere. The position of the mercury in the tube is marked off at each of these standards of reference. To determine the freezing point, the instrument is plunged into a vessel containing pounded ice, or snow in a melting state; the mercury sinks in the stem, and at last settles at a particular level; a scratch is made on the glass corresponding with this position.

The boiling point is more difficult to determine accurately. For this purpose an apparatus like that represented sectionally in fig. 168 must be used. It is constructed of copper. A central tube A runs up from the vessel C in which water is placed. This is surrounded by a cover B, made fast to the lower vessel, and having an escape pipe D. The thermometer is introduced through an aperture at the top, closed with a well-fitting cork. The apparatus is placed upon a furnace and the water made to boil, the steam generated passes up the central tube, then into the hollow space surrounding it, and eventually finds an exit by the tube D. A considerable amount of condensation necessarily takes place at first, especially in the cover B, exposed as it is to the cool outer air; but, after a time, the thermometer is encircled with steam of the same temperature as that immediately escaping from the water, and the mercury rises and settles at a particular level. This new level, as before, is marked off on the stem.

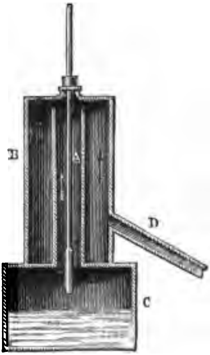


Fig. 168.—Determination of Boiling Point.

The immersion of the instrument in *steam*, and not in the water itself, is rendered necessary by the fact that water has been found to boil at different temperatures depending upon the *material* with which the vessel is constructed, whilst the temperature of the steam remains unaffected.

The interval between the two positions of the mercury thus determined is then divided into so many equal parts.

194. Thermometric Scales.—The interval just mentioned is differently divided in different countries, giving rise to the

three common forms of the thermometer. These are named from the inventors, and are known as the *Fahrenheit*, *Celsius* or *centigrade*, and *Réaumur*. In Fahrenheit (fig. 169) the freezing point is marked 32 (a zero being taken which was incorrectly imagined to be the greatest cold obtainable), and the boiling point 212; in centigrade these points are marked respectively 0 and 100; and in Réaumur, 0 and 80. The space, therefore, between the two fixed points is divided in F. into 180 equal parts, in C. into 100, and in R. into 80. Each of these parts is called a degree.

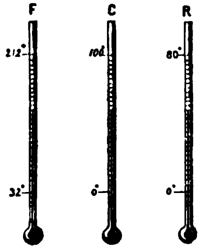


Fig. 169.—Thermometric Scales.

A temperature below 0° in any of the scales is indicated by a minus placed before the number. Thus − 10° C., indicates 10 degrees below the freezing point, according to the centigrade scale; and again, − 10° F., 10 degrees below 0°, according to the Fahrenheit scale.

It is found that even after a thermometer has been constructed with the greatest care its indications are liable to derangement; this results from the bulb not resuming its former capacity after being strongly heated, and it is not till after several months that the instrument can be regarded as altogether trustworthy.

When delicacy of observation is required, new instruments ought to be compared with a reliable standard thermometer, and a table of corrections drawn out for the different readings.

195. Conversion from one Scale to another.—The student ought now to have little difficulty in understanding how to solve questions in connection with the conversion from one scale to another.

Calling F, C, and R the three scales, we have

$$F : C : R :: 180 : 100 : 80 = 9 : 5 : 4; \text{ hence,}$$
$$(1)\ F = \tfrac{9}{5}C; \quad (2)\ F = \tfrac{9}{4}R; \quad (3)\ C = \tfrac{5}{4}R.$$

By means of these three formulæ, it is easy to solve any question connected with the subject. It must be borne in mind, however, that to convert F degrees into C or R degrees, 32 must be subtracted *before*, and in the converse problem

added *after*, formula (1) or (2) is applied. We give the following examples by way of illustration:—

EXAMPLE I.—Convert 86° F. into the centigrade scale.

$$86-32=54.$$

By formula (1) $C=\frac{5}{9}F=\frac{5}{9}\times 54=30°$;

hence $86°$ F$=30°$ C. *Ans.*

EXAMPLE II.—Convert $-25°$ C. into the Fahrenheit scale.

$$F=\tfrac{9}{5}C=\tfrac{9}{5}\times -25=-45;$$

and adding 32 we have

$$-45+32=-13;$$

hence $-25°$ C$=-13°$ F. *Ans.*

EXAMPLE III.—How many degrees of F. are equivalent to 16° R.?

By formula (2) $F=\frac{9}{4}R=\frac{9}{4}\times 16=36$.

Add 32, we have 68; hence 16° R$=68°$ F. *Ans.*

EXAMPLE IV.—How many degrees of R. are equivalent to $-5°$ C.?

By formula (3) $R=\frac{4}{5}C=\frac{4}{5}\times -5=-4$;

hence $-5°$ C$=-4°$ R. *Ans.*

196. Maximum and Minimum Thermometers.—These instruments are adapted to record the greatest heat or highest temperature which has been reached during the day, and the greatest cold or lowest temperature which has taken place during the night, hence the names. Fig. 170 exhibits com-

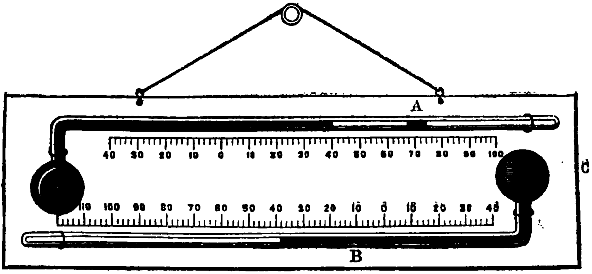


FIG. 170.—MAXIMUM AND MINIMUM THERMOMETERS.

mon forms of the two instruments. They are fixed on a rectangular frame of plate-glass, which is adjusted so as to hang horizontally. The upper one—the maximum thermometer—is filled with mercury; the other with coloured alcohol. In the former there is a piece of iron wire A, which is pushed along the tube by the mercury as the temperature

rises. On the temperature falling, it does not follow the mercury, but remains at the part of the tube to which it was moved. The greatest heat, therefore, is obtained by reading off the degree on the scale opposite the end nearest the mercury. In the minimum thermometer there is a small tube of glass, B, which serves as the index. As the temperature falls the fluid contracts and draws with it the small index, owing to the attraction of adhesion. When the temperature rises the fluid passes round and through the small tube, but does not push it forward. The lowest temperature, therefore, is obtained by reading off the degree at the extremity of the index next the end of the column. To make an observation, the glass plate must be held vertically, with the end C uppermost, so as to move the indices A and B to the end of their respective columns, and then suspended in a horizontal position.

Both instruments are of great service in meteorological observations; the latter is much used by farmers, gardeners, etc.

197. Method of finding Temperature in Inaccessible Places.—In certain cases, as for example in the determination of the temperature at different depths in the sea, the thermometer cannot be directly applied. An ingenious method of ascertaining the temperature of a place at which it is impossible to set a thermometer has been invented by Siemens, and successfully applied by him. It depends on the principle that the electric resistance of metals is in proportion to the increase of temperature. "Two coils of the same kind of fine platinum wire are prepared, so as to have equal resistance. Their ends are connected with long, thick copper wires, so that the coils may be placed, if necessary, a long way from the galvanometer. These copper terminals are also adjusted so as to be of the same resistance for both coils. The resistance of the terminals should be small as compared with that of the coils. One of the coils is then sunk, say to the bottom of the sea, and the other is placed in a vessel of water, the temperature of which is adjusted till the resistance of both coils is the same. By ascertaining with a thermometer the temperature of the vessel of water, that of the bottom of the sea may be deduced."*

* Maxwell on *Theory of Heat*, p. 53.

CHAPTER III.

EBULLITION—FUSION—CONGELATION.

198. Boiling of a Liquid.—The process by which water is raised to the boiling point is a very interesting one. Thus, let an open flask of water be exposed to heat, as in fig. 171. The stratum of fluid at the bottom, in becoming heated, expands and rises to the surface; another stratum taking its place, in like manner expands and rises, and so on successively. There are produced, therefore, in the vessel a series of ascending warm currents and of descending colder currents, and this circulation continues until the water is nearly brought to the boiling point. When this point is reached, bubbles of gas are observed to form themselves next the heating source. These at first, in their passage upwards through the colder water above, are gradually condensed, and diminishing in volume as they ascend scarcely reach the surface; but in proportion as the *whole* water approaches the boiling point this condensation ceases, and the bubbles escape at the surface as steam. The water is then said to *boil.*

Fig. 171.—Ebullition.

199. The Dependence of the Boiling Point upon External Pressure.—The temperature at which water boils

in an open vessel is dependent upon the pressure or the atmosphere. At the ordinary pressure, that is, when the barometer indicates about 30 inches of mercury, the boiling point is 212° F. If the pressure diminish, the boiling point falls; on the other hand, if the pressure increase, it rises above the temperature of 212°. Hence the necessity of strictly defining what the *boiling point* of a liquid really is. It is *that point of temperature at which the tension or elastic force of its vapour is exactly equal to the pressure it supports.*

The variation of the boiling point of water with the pressure will be seen from the following table:—

Height of the Barometer. (Inches).	Boiling Point. (Fahrenheit).
17·04	185°
18·99	190°
21·12	195°
23·45	200°
25·99	205°
28·74	210°
29·33	211°
29·92	212°
30·51	213°
31·73	215°

From this table it appears that a variation of $\frac{1}{10}$ of an inch of the barometer causes a difference of about $\frac{1}{6}$ of a degree Fahrenheit in the boiling point; hence the range of the boiling point in our climate may be as much as 5°, with the ordinary variations of the barometer.

In a *closed* vessel, water may be raised to a much higher temperature than 212°. This is the case in the boiler of a steam-engine, or of a locomotive. By the accumulation of the steam the pressure on the water is increased, the boiling point is therefore raised, or the water is heated above its ordinary boiling point. Under a pressure of *two* atmospheres, water is found to boil at a temperature of about 249° F.

200. Illustrations.—A striking illustration of the dependence of the boiling point upon external pressure, is to take a vessel of hot water, put it under the receiver of the air pump, and exhaust the air. In a short time the water begins to boil, and as the rarefaction goes on, the ebullition increases in intensity.

Another experiment consists in taking a vessel of hot water (fig. 172), corking it up, and then inverting it. If now cold water be allowed to fall over the confined vapour, it partially condenses it; the water in the vessel, therefore, is so far relieved from pressure, and in consequence enters into a state of ebullition.

Fig. 172.—LOWERING OF BOILING POINT.

201. Measurement of Heights by the Boiling Point.— It can be understood from Art. 199, that it is possible to determine the height of a mountain by means of the boiling point. Knowing the amount of variation in the boiling point with the fall of the barometer, and the relation this latter bears to the ascent, we can, of course, determine at what rate the boiling point falls for so many feet of perpendicular ascent. It appears that the boiling point is lowered 1° F. for about 590 ft. of elevation. All that is necessary, therefore, is to ascertain what the boiling point is at the top of the mountain, and allow 590 ft. for every 1° F. below 212°. Thus, if the boiling point be 206°, the height of the mountain would be $590 \times 6 = 3540$ ft.

An instrument has been invented for this purpose, called a *thermo-barometer* or *hypsometer.* The method, however, is capable of giving only an approximation to the real height.

202. Papin's Digester.—In consequence of the lowering of the boiling point, it becomes necessary, in the ascent of high mountains, to have an apparatus for the proper cooking of food. A common form of such an apparatus is "Papin's Digester." It consists of a metallic vessel with a cover held down by a screw, working through a strong collar attached to the top of the instrument. There is an aperture in the cover into which a valve fits; the valve is fixed to a lever, which moves round a fulcrum on the collar, and which carries at its other end a weight—an arrangement similar in principle to that of the safety-valve in the steam engine. The valve being held in its place by the adjusted weight, the steam as it is generated accumulates, and thereby exerts sufficient pressure on the water to raise its temperature above that at which it would boil, were the vessel open.

203. Boiling Point otherwise affected than by Pressure.—It has been found that the boiling point is affected by the *kind* of vessel. Thus it appears that water contained in a glass vessel requires to be raised to a higher temperature to boil than in a metallic one. Whatever be the variation, however, in the boiling point from this cause, it is found that the temperature of the *steam* remains unaffected.

The boiling point of water is also affected by the quantity of air absorbed in it. Thus water previously freed from air by ebullition, may be raised several degrees *above* its ordinary boiling point before it actually boils. Moreover, a substance in solution, or a mixture with some other liquid, has an effect. Thus water saturated with common salt boils at a temperature of 228° F. Again, when it is mixed with the bisulphide of carbon, the boiling point is much reduced. If both be mixed, for example, at a common temperature of 81° F., the mixture begins to boil briskly.

204. Boiling Points of other Liquids.—The boiling points of liquids vary considerably. But it is important to observe that they, like that of water, are influenced by external pressure, and remain *constant* during the whole process

of ebullition. We append a table, showing the boiling points of some liquids, under the ordinary atmospheric pressure:—

BOILING POINTS OF LIQUIDS (Centigrade).

Sulphurous acid	−10°
Ether	+37°
Bisulphide of carbon	48°
Alcohol	79°
Spirits of turpentine	130°
Sulphuric acid (concentrated)	325°
Mercury	350°

205. Fusion.—A solid body can remain solid only so long as the heat to which it is subjected is kept within a certain limit. If this limit be reached or exceeded, the body undergoes a change of state, *fusion* sets in—in other words, it becomes liquid. The temperature at which this change of condition takes place is called the *melting point.* Some bodies, such as wood and stone, instead of melting, when subjected to a high temperature, are decomposed. Others seem to resist being liquefied even under the greatest heat we are capable of producing. We have an example of this in carbon; an amount of heat, however, has been brought to bear upon it sufficient to render it *flexible*—a state bordering upon the liquid.

In most cases there is a definite melting point for each substance, the body passes quickly from the solid to the liquid state. The most familiar example is lead. In other cases again, such as in glass and iron, the transition is gradual, and no definite melting point can therefore be assigned.

The following table gives the melting points of certain substances:—

MELTING POINTS (Centigrade.)

Butter	33°	Zinc	360°
Phosphorus	44°	Pure silver	1000°
Sodium	95°	Copper	1150°
Sulphur	110°	Pure gold	1250°
Tin	230°	Wrought iron	1500° to 1600°
Lead	320°	Platinum	2000°

206. Maximum Density of Water.—If a quantity of water, say at the temperature of 62° F. (standard temp.), be gradually cooled down, it contracts until it reaches the

temperature of 39·4°, when all further contraction ceases. This point is called the point of *maximum density*. When cooled below this temperature, *expansion* sets in, which increases rapidly as the freezing point is approached. Water is therefore *heaviest* at the temperature of 39·4° F. or 4° C. For example, a cubic foot of water at this temperature weighs more than a cubic foot at any other temperature.

207. Deportment of Water in Freezing.—When water freezes, it undergoes a sudden expansion. The amount of its expansion is found to be about 10 per cent.; more exactly, 1000 cubic feet of water at the freezing point become 1102 cubic feet of ice at the same temperature.

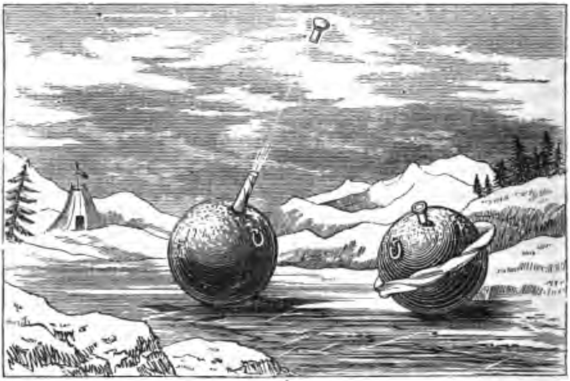


Fig. 173.—Expansion in Freezing.

The force of this expansion is almost irresistible. A strong iron bottle filled with water, and firmly closed, when immersed in a freezing mixture, is rent asunder in a short time. Some interesting experiments on this point were made one severe winter at Quebec by Major Williams. He took a bomb-shell, and having filled it with water, carefully plugged up the aperture; on exposing it to the frost, the plug was driven to a distance of 330 feet, whilst at the same time a cylinder of ice $8\frac{1}{2}$ inches long appeared protruding at the aperture (fig. 173). In another experiment, the plug being more firmly fixed, the bomb was ruptured at the middle, and a ring of ice was forced through the rent.

The common accident of the bursting of pipes in frosty weather, can therefore be easily understood. The rupture takes place, of course, during the frost; but the rent being closed up with ice, no leakage of water takes place. It is only when the thaw sets in that the damage done to the pipe becomes apparent.

We can understand also what takes place when a lake is being frozen over. Suppose the average temperature of the water to be 45° F., and that frost suddenly sets in, the layer next the cool atmosphere contracts, and thus increasing in density sinks to the bottom; it is succeeded by another layer, which in turn being chilled, becomes heavier and sinks. The same thing is repeated with layer after layer until the whole water is brought to a temperature of 39·4°, at which point the transfer of the liquid particles will cease. After this, expansion begins at the superficial layer, which goes on at an increasing rate till the freezing point is reached, when crystallization commences, and ice is formed. As the frost continues, the ice increases in thickness, because of its chilling power on the contiguous layers, and its conductivity of the cool temperature outside. During a severe frost, it often happens that the ice is rent in several places with long cracks; this is due to the contraction which has taken place on the part of the ice, resulting from the low temperature.

Water, though the most familiar instance of a body expanding on solidification, does not stand *unique*. We have an instance of the same thing in bismuth. Thus if a metallic bottle be filled with molten bismuth, and firmly plugged up, the bottle is ruptured when the metal solidifies.

208. Effects in Nature.—In the economy of nature the expansion which accompanies the freezing of water exerts a most important agency. Had water, in cooling, observed the general law of contraction, then a layer of ice when formed on the surface of our lakes or rivers would have sunk to the bottom; another would have been formed, and in like manner have sunk to the bottom, and so on until the whole water had become one solid mass of ice, which all the influence of a summer sun could scarcely have dissolved. As it is, however, these effects are happily prevented. The ice being

lighter than the water floats on the surface, and thus the water below, being sheltered from the cold atmosphere above, preserves its liquid form.

It is thus also that our soils are pulverised during winter. The water they imbibe, upon freezing, disintegrates them, and thereby assists, in no small degree, the labours of the husbandman in preparing them for the reception of the seed. Hence, during frost, the soil is observed to have a cracked appearance.

209. Regelation.—If two pieces of ice just at the point of fusion be laid on each other, freezing at once sets in, and the two pieces are so knit together, that, by taking hold of the upper one, the lower may be lifted. This effect was first noticed by Faraday, and is now known as "*regelation*"—a term suggested by Tyndall.

Regelation may even take place in hot water. Thus, for example, if several small pieces of ice be set floating in a dish of hot water, and the series be brought into contact, the whole may be lifted out of the dish by laying hold of the terminal one.

This explains how, even on a hot summer's day, pieces of ice in a fishmonger's window cling together when brought into contact. It is well known to young people that the best time to roll large snow-balls, or make snow-figures, is when the thaw has set in. During frost, the snow is crisp, and refuses to stick together, but on the occurrence of a thaw, it can be moulded into any desired shape. The effect is due to regelation.

210. The Freezing Point affected by Pressure.—Theoretical considerations, based on the mechanical theory of heat, lead to the conclusion that a body which expands on solidifying should have its freezing-point *lowered* by external pressure. Such is found to be the case by actual experiment. Sir W. Thomson found that with a pressure of 9·1 atmospheres the freezing-point of water was lowered by 0·106° F., and with a pressure of 17·8 atmospheres, by 0·232° F. Subsequently, Mousson invented an apparatus by which he could obtain several thousand atmospheres of pressure, and, by it, he succeeded in lowering the freezing point several degrees. The ordinary variations in the atmospheric pressure exercise no appreciable effect.

On the other hand, according to theory, a body which expands on melting should have its melting point *raised* by pressure; this result has also been proved experimentally.

Bunsen and Hopkins have shown that wax, sulphur, stearine, and paraffin, melt at a higher temperature under pressure than they otherwise would do.

211. Retardation of the Freezing Point.—Water, if *kept perfectly still*, may have its temperature reduced considerably below its ordinary freezing point before it congeals. On the least motion, however, being imparted to the vessel containing it, or if a small piece of ice be made to touch the surface, the whole of the fluid at once solidifies. By the water being kept at rest, a temporary check, as it were, is put upon the act of crystallization; the molecules seem to refuse to assume a crystalline condition, and it is only after mechanical disturbance that the solidification proceeds.

By using capillary tubes, Despretz succeeded in cooling water as low as $-20°$ C., without freezing. This interesting result helps to explain why plants can withstand severe frost without being damaged—the juices, confined as they are in the tissues, remain in their liquid state, notwithstanding the low temperature of the external atmosphere.

When solidification occurs in such cases there is a disengagement of heat, and the ice thus formed rises to its ordinary freezing point. A striking experiment on this point may be made with the hyposulphite of soda—a white crystalline salt much used in photography. The substance melts at a temperature of 134° F., but when allowed to cool, without shaking the vessel, it remains in the liquid state, even down to the standard temperature of the atmosphere. On agitating it, however, or sprinkling a few crystals of the salt on the surface, it solidifies, and a very perceptible rise of temperature may be felt by the hand.

CHAPTER IV.

EXPANSION OF GASES—WINDS.

212. What is implied by the Expansion of a Gas?—The expansion of gases exceeds that of either solids or liquids, and is *almost* uniform; that is, the amount of expansion is found to be nearly in proportion to the increase of temperature. The process of dilatation, or contraction of gases, does not take place in the same manner as in solids and liquids. Let us suppose, for instance, that we have a glass receiver closed on all sides, and filled with air of the same density as that of the external atmosphere. If the temperature of this enclosed air be lowered, it will not contract in its dimensions, it will still occupy the *whole* of the receiver, but its elastic force is reduced; in other words, it will not exert the same pressure on the containing vessel as before, and were the external pressure of the air allowed to act, it would force the confined air into a smaller space. In like manner, suppose the air contained in the receiver to be subjected to an increase of temperature, then the elastic force of the air is increased, and were the receiver to offer no resistance, it would expand and occupy a greater space.

By gases expanding or contracting by a change of temperature, is therefore meant that they do so under a *given pressure* —the pressure generally taken being the *ordinary pressure of the atmosphere.*

213. Experimental Illustrations.—(1) A bladder partly filled with air and closed up, when held before a fire, becomes gradually inflated, shrinking to its former dimensions on its removal. (2) When a flask of water, as in fig. 171, is at first heated, bubbles of air are seen to rise through the water, owing to the expansion of the air-particles which have been absorbed by the water. This is more strikingly seen with

ale or other fermented liquor; a quantity of froth collects on the surface in proportion as the gaseous particles are liberated. Hence, when a bottle of such liquid is placed before a fire, it often happens either that the bottle is broken, or the cork driven out with a loud report. (3) A flask, A, containing air, is taken (fig. 174), from which a bent tube is led to a dish B filled with coloured water. Over the end of this tube is placed an upright tube C, previously filled with the fluid and inverted. If now the flask be heated by a spirit lamp, the air inside expands, passes through the bent tube, and collecting in C, gradually displaces the fluid, and eventually expels it entirely.

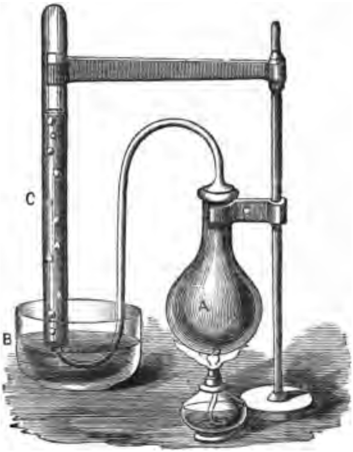


Fig. 174.—EXPANSION OF AIR.

214. Constancy of the Co-efficient of Expansion.—The co-efficient of expansion of all the *permanent* gases, that is to say, those which resist liquefaction by pressure, is found to be nearly the same. Different physicists agree in assigning as the co-efficient (between 0°C. and 100°C.) the fraction $\cdot 00366 = \frac{11}{3000}$ nearly, under a variation of pressure of from 12 to 20 inches of mercury. The co-efficient is found to increase with the pressure to a small extent, the temperature being the same. By ordinary variations of atmospheric pressure, however, it is virtually unaffected.

Adopting the fraction $\frac{11}{3000}$, as the approximate value of the co-efficient, we see that a gas occupying 3000 cubic inches at 0° C., would occupy 3011 cubic inches at 1° C., 3220 at 20° C., and 4100 at 100° C., supposing the envelope containing the gas to be at liberty to expand.

If, however, the containing vessel be a rigid one, how are we to estimate the expansion with the rise of temperature?

The expansion now resolves itself into an *increase of pressure* on the sides of the vessel. The following example will sufficiently illustrate the method:—

EXAMPLE.—Let the receiver, as before, contain 3000 cubic inches of air at 0° C. If heated 10° C., the volume tends to become 3110 cubic inches, but seeing that the receiver is rigid, the 3110 cubic inches are compressed into the space of 3000 cubic inches. According to Boyle's law, therefore, the pressure on the receiver will be increased in the proportion of 3000 : 3110; hence, taking the barometric pressure at 30 inches of mercury, we have

$$3000 : 3110 :: 30 : x;$$
$$\therefore \quad x = 31 \cdot 1;$$

that is, the pressure of the contained gas is now equivalent to 31·1 inches of mercury, or which is the same thing, the increase of pressure from the heat is measured by 1·1 inches of mercury.

The converse problem is also susceptible of easy solution, as shown in the following example:—

EXAMPLE.—To what temperature must a gas occupying 1500 cubic inches at 10° C. (barom., 30 in.) be heated, so that the pressure on the receiver may be increased by 5 in.?

Here we must first state thus

$$30 : 35 :: 1500 = 1750;$$

this is the volume the gas would assume under the required temperature, were it free to expand.

Now, as $\frac{11}{3000}$ of 1500 is the increase for 1° C., we have, therefore,

$$\tfrac{11}{3000} \times 1500 : 250 :: 1 = 45\tfrac{5}{11};$$

and hence the temperature required

$$= 10 + 45\tfrac{5}{11} = 55\tfrac{5}{11}° \text{ C. } \textit{Ans.}$$

215. Carbonic and Sulphuric Acid Gases.—The co-efficient is found to be somewhat greater in the case of those gases which can be liquefied. The most notable of these are carbonic acid and sulphurous acid; careful experiment gives their co-efficients at ·00371 and ·00390 respectively. A few words may be added as to the physical character of these gases.

CARBONIC ACID (CO_2).—This gas is one-half heavier than common air; it is colourless, but possesses a slight odour, and a perceptibly sour taste. Its principal chemical feature is that it extinguishes flame, and causes death to an animal inhaling it. It is present in the atmosphere, and in the

water of many mineral springs. The quantity present in free air is nearly constant, amounting to about 4 volumes in 10,000 of air. Small as this appears to be, it is nevertheless sufficient and necessary for the support of vegetable life.

Carbonic acid is given off by animals in respiration and by combustion. Fermented liquors, soda water, etc., owe their sparkling briskness to the escape of this gas. It may be liquefied at a pressure of about 36 atmospheres. The liquid possesses the remarkable property of being more expansible that the gas itself—a strange exception to the rule that liquids expand less by heat than gases.

SULPHUROUS ACID (SO_2) is given off when sulphur is burnt, and in large quantities from volcanoes. It is colourless, but possesses a suffocating smell of burning sulphur. It is $2\frac{1}{4}$ times as heavy as air, and is reduced to a liquid at a pressure of two atmospheres, or by being cooled down to $-10°$ C. under the ordinary atmospheric pressure.

216. Draft of Chimneys—Ventilation.—When a fire is kindled in a room, the flame and warm smoke proceeding from it soon raise the temperature of the air in the chimney. The consequence is, it ascends, and the colder air from the room flows in to supply its place; this air, in turn, likewise becoming heated, rises, and a fresh accession of air takes place, and so on.

What constitutes, therefore, the *draft* of a chimney is nothing else than the colder air of the room constantly passing towards the fire-place.

As the air in a room is continually passing towards the fire, there must of course be a constant supply kept up from the external air, which must therefore have sufficiently free access by the doors and windows of the house. Hence it is found that in a house where the passage of the external air is much interrupted, the chimneys are liable to smoke, the reason being that a sufficient draft is not maintained.

At the door of a room where there is a fire there are two opposite currents of air, the heated air in the room ascends to the top and passes out at the upper end of the door, whilst the colder air from without enters by the lower part. This may be easily proved by placing a lighted taper in these positions at the outside of the room door. In the former

position the flame is bent *from* the door, and in the latter *towards* it.

When all the windows and doors of a house fit so closely as to impede a communication with the external air, and thus prevent a sufficient supply for the fires in the house, the necessary quantity descends by those chimneys which are not in use. Hence, when a fire is being lighted in any of these, the smoke at first is driven into the room. To remedy this, the room door ought to be shut, or the window opened; this being done, the chimney will soon begin to *draw*. What is called *back smoke* in a room where there is no fire arises from the circumstance that the chimney is serving as an inlet for air to supply the fires in the house, carrying the smoke of a neighbouring chimney down into the room along with it.

The grand object in *ventilation* is to allow the heated air, or air vitiated by respiration, to escape at the roof of the building, whilst provision is made at the same time for an inlet of fresh air, the whole arrangements being such as to obviate drafts. The principle of ventilation is strikingly illustrated by the following simple experiment: A glass receiver (fig. 175), with an aperture at the top, is placed over a candle put into a flat dish, in which there is water. In a short time the air in the receiver becomes vitiated by the combustion, and the candle flame, gradually dwindling down, is at last extinguished. If, however, the candle be relit and a card be placed in the funnel, or chimney, thus dividing it into two parts, the candle continues to burn, preserving its brightness almost unimpaired. The reason of this is, that the vitiated air now escapes through one of the passages, whilst fresh air gets in by the other, as indicated by the arrows.

Fig. 175.

7. Winds—General Character of.—The phenomena of

winds, in general, result from *the unequal distribution of heat over the earth's surface.* It is ascertained, for example, that the *mean* temperature at the equator is 84° F., at 78° north latitude 16° F., and at the pole it has been inferred to be about 4° F.

The principle has been adopted by meteorologists of laying down on the earth's surface lines passing through places which have the same *mean* temperature for the year. These lines are called "*isothermal lines*," or, more simply, "*isotherms*." In many places they are by no means parallel to the different parallels of latitude, but are inclined to the latter at very considerable angles. The departure from parallelism is signally remarkable in the neighbourhood of Great Britain and Norway; the lines in these regions indicate the same mean annual temperature as those passing through places in Asia or America, lying from 10° to 20° further south.

From such diversity, then, of temperature in different portions of the earth's surface, it is impossible that the atmosphere can remain calm and unaffected. When any region becomes more heated by the sun's beams than some other, the air above it also gets heated and rises up, whilst the colder surrounding air rushes in to supply its place, and the atmosphere is more or less disturbed. Hence arise those perturbations to which we give the name of "winds."

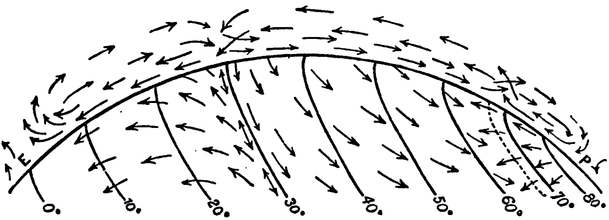


Fig. 176.

The accompanying illustration (fig. 176) gives a general view of the character of the winds which prevail in the northern hemisphere, from the equator to the pole. The arrows show the direction of the aërial currents. The warm air from the tropics, ascending to a certain height in the atmosphere, flows northward as an upper current; on cooling

down it descends about the 30th parallel of latitude, and blows as a south-west wind between that parallel and the 60th; getting warm by contact with the earth's surface, it again ascends, still flowing towards the pole, where it at length precipitates itself and forms the polar gales. Returning now southwards, it ascends at the 60th parallel, blowing as an upper current, till, on getting chilled, it descends at the 30th parallel, and, between that and the equator, blows as a north-east wind. Thus a continuous circulation of air goes on.

It must be understood, however, that these aërial currents are subject to considerable variation, swayed as they are by a number of disturbing influences which more or less affect them.

218. Velocity of Wind—Anemometer.—The velocity of the wind depends upon the degree of rarefaction which has taken place in that portion of the atmosphere towards which the current of air is moving. It is measured by an instrument called an *anemometer*. A common form of the instrument, and one adapted to give accurate results, consists of four hemispherical cups attached to the extremities of four equal arms made fast to a vertical spindle. At the other end of the spindle is an endless screw, which is connected with a train of wheel-work similar to what obtains in the common gas-meter. As the cup-vane rotates by the wind, the indices move round their respective dials, and by noting the number of revolutions they severally perform in a given time, the velocity of the wind is inferred. The following table will give a general idea of the relation between the velocity and the character of the wind:

VELOCITY OF WIND.

Miles per Hour.	Observations.
1	Hardly perceptible.
5	Gentle, pleasant wind.
15	Gale.
20	Brisk gale.
30	Storm.
40	Tempest.
50	Hurricane.
80 to 100	Violent hurricane.

The pressure per square foot may be approximately esti-

mated by a convenient formula, founded upon an elaborate series of observations. If p express the pressure in lbs. and v the velocity in *feet* per second, then $p = \cdot 002214v^2$. Applying this to the case of the violent hurricane that passed over Edinburgh on the 24th Jan. 1868, on which occasion the velocity, as determined by the anemometer, was estimated at 90 *miles per hour*, we find the pressure per square foot to be 38·5 lbs. This result nearly agrees with the estimate of 40½ lbs. as determined at the time, by other means.

219. Trade Winds.—The *trade winds*, so named from their importance to navigation, and hence to the purposes of trade, are those which prevail in the tropics. They blow in the northern hemisphere from the *north-east*, and in the southern hemisphere from the *south-east*.

They are easily accounted for. In consequence of the high temperature of the tropics, there is a continual uplifting of heated air from that region, whilst the colder air from the temperate zones rushes in to supply its place. Now, were the earth stationary on her axis, this colder air would come directly from the north and south; that is, there would be a north wind in the northern hemisphere and a south wind in the southern. But the earth is in a state of constant revolution from west to east, and from her configuration it is clear that the different points in her surface have very different rates of motion. The colder air, therefore, in its passage towards the equator, will move over latitudes which are gradually increasing in velocity. It cannot acquire all at once the velocity of that part of the earth over which it is advancing. It must necessarily lag behind, and be *struck* by the objects in that zone with a certain force. Thus, that air is influenced by two motions; *first*, a northerly or southerly motion, caused by its tendency to rush to the equator to supply the place of the heated air there; and *second*, an easterly motion, caused by the rotation of the earth.

By a well-known principle in dynamics * the air will obey

* The principle here referred to is the "parallelogram of motion." If a point A is urged by a force which would make it move over the space AB in a certain time, and by another force over AC in the same time, then completing the parallelogram, the point under the influence of the two forces will move through the diagonal AD.

neither the one motion nor the other, but will take an intermediate course. In other words, the wind will blow from the north-east in the one case, and south-east in the other.

The following familiar illustration may be given: Suppose a horseman to gallop along towards the east on a quiet day, his motion will give rise to a certain resistance on the part of the air, and he will imagine that an east wind is blowing; but let him do the same thing when a slight north or south wind is blowing, his motion will give an easterly character to either wind, and he will judge of the wind as coming from the north-east or south-east. There is a similar effect in the trade winds.

The *region* of the trade winds in both hemispheres is subject to change of position. This results from the passage of the sun north or south of the equator. At the summer solstice this region is wholly carried north of the equator, at the winter solstice it is carried considerably south, but does not entirely pass the equator. This is due to the fact of the preponderance of land in the northern hemisphere.

It is also worthy of remark that the "trade winds" *change sensibly in direction* as they approach the equator. At their limit in either hemisphere they blow almost directly from the east, and gradually lose their easterly character as they proceed towards the equator. This results from the fact, that the *difference* of velocity between the different parallels of latitude becomes less and less. Thus the 30th parallel moves with a velocity about 80 miles less than the 20th—the 20th with a velocity of 46 miles less than the 10th, and so on. In consequence of this the current travelling between the 30th and 20th parallels will be more left *behind* by the earth than that travelling between the 20th and 10th, hence the objects in the former one will strike that air with a greater force than those in the latter, giving rise to a more easterly character in the wind in the former region than in the latter.

220. Monsoons.—What are called "monsoons" are modifications of the "trades." They are due to the presence of vast masses of territory. They prevail with great regularity between India and the eastern coast of Africa. From about October to April they blow from the north-east, and from April to October from the south-west. They are thus

accounted for: When the sun is far south, the air is heated in the neighbourhood of the equator to a greater degree than that over the great continents of India and China; a transfer of the colder air thus ensues, which, combined with the earth's rotation, causes a north-easterly wind—continuing till the sun passes the equator on his way northward. Proceeding on his course north of the equator, a greater amount of heat is imparted to the air above these continents than to that above the equatorial zones. The consequence is, that the cooler air of the equator rushes northward, and passing into regions moving slower, there is produced the south-west monsoon. During the change in their direction, a period known among mariners as "the breaking up of the monsoons," storms and variable winds generally occur.

221. Land and Sea Breezes.—The *land* and *sea-breezes* are peculiar to maritime localities. During the night the land loses its heat by radiation more rapidly than the sea; the cool air from the land therefore makes its way to the sea, displacing the warmer air there. This constitutes the land breeze. During the day the reverse takes place; the cool air from the sea flows to the land, forming the sea-breeze. The beneficial effects of the sea-breeze are particularly felt in tropical climates. Many islands would be almost uninhabitable were it not for the sanitary influence of this breeze.

Even in our own country the pleasant cooling effect of the sea breeze is perceptibly felt, more especially near our coasts, on a sultry day, when the land gets so much heated as to cause an uplifting of the warm air, and a consequent inrush of the cooler air from the sea.

CHAPTER V.

AQUEOUS VAPOUR—RAIN—SNOW.

222. Evaporation.—This is the process in virtue of which vapour passes imperceptibly from the surface of a liquid when exposed to the air. Liquids differ much from each other in this respect. A liquid in which evaporation takes place freely is said to be *volatile*. Thus a drop of ether let fall upon the hand will disappear more rapidly than a drop of water. Ether, therefore, is a more volatile liquid than water.

That this process is in constant action is proved from many familiar facts. A tumbler of water put outside a window in dry weather gradually loses its contents. No sooner are our streets watered than they begin to dry. Wet clothes, hung up in an open place, soon lose their moisture.

The rate at which evaporation takes place depends upon the temperature; the higher the temperature, the more rapid the evaporation. Hence the rapidity with which roads are dried in summer after a shower of rain. A wet towel, placed before a fire, is soon dried. Our rivers are much diminished in size after a continuance of fine weather. On the other hand, a low temperature so far checks evaporation; but for each liquid there seems to be a temperature below which evaporation virtually ceases. Thus little or no evaporation can be detected from mercury at 0°C., or from strong sulphuric acid at the ordinary atmospheric temperatures.

Evaporation takes place also from certain solids. A piece of ice, for example, when exposed to severe frost, is found to diminish sensibly in bulk. So also camphor, when exposed to ordinary temperatures, passes at once from the solid to the gaseous state.

223. Aqueous Vapour—Point of Saturation.—In consequence of evaporation constantly going on from the surfaces

of our rivers, lakes, and seas, at all temperatures, our atmosphere is always charged with aqueous vapour. By *aqueous vapour* we are to understand not fog, cloud, or mist, but water in the state of an impalpable transparent gas.

From what has been stated in the previous Article, it is clear that the quantity of aqueous vapour will depend upon the temperature, and that a continuance of fine weather in any locality is favourable to the production of a large supply. Moreover, it can be readily imagined, that even throughout the same day, owing to the varying power of the sun, the quantity carried aloft may vary. Though there is considerable difference in the capability of the air as regards the suspension of aqueous vapour for different temperatures, there is for each temperature a definite quantity which can be elevated. When air has reached this state it is said to be *saturated*, or to have attained its *point of saturation*. Thus, if there are two equal masses of air, of 40°F. and 70°F. respectively, each can take up its own definite quantity of vapour; but the former, owing to its lower temperature, will reach its point of saturation sooner than the latter.

The presence of watery vapour in the air is proved by the familiar fact, that if a bottle of wine be brought from a cool cellar in summer, and exposed to the air of a room for some time, the surface of the bottle becomes quite moist. This is owing to the contiguous air being so chilled as to cause condensation.

The quantity of aqueous vapour in the atmosphere, at ordinary temperatures, is small. It has been estimated that in 100 parts, there are only ·45 parts of aqueous vapour, the remaining 99·55 parts consisting chiefly of oxygen, nitrogen, and carbonic acid gases.

224. Tension of Vapours.—The elastic force or *tension* of a vapour is measured by the number of inches of mercury which it can support in a barometer tube. A suitable apparatus for this purpose is represented in fig. 177.

Two barometric tubes, communicating with each other, are mounted on a stand B. Mercury being poured into the longer tube, whilst the other is kept open, it stands at the same level in both. A glass vessel A is connected with the shorter branch by an india-rubber tube. This vessel, pro-

vided as it is with a metal cup, is also mounted with two stop-cocks C, D. The upper one D, shown separately in the figure at E, is perforated only half-way through, and is fitted with a conical cup. To use the apparatus, the stop-cock D is removed, and the vessel is then put in connection with an air-pump and exhausted. The effect of this is to cause the mercury to rise in the left hand tube. D is now screwed on and the cup filled with liquid. By opening C, and turning D backwards and forwards several times, the liquid is intro-

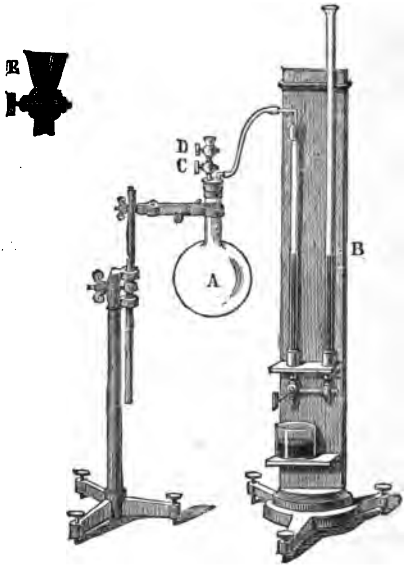


Fig. 177.—Apparatus to Determine the Tension of Vapours.

duced into the flask, without, at the same time, allowing any air to enter. The liquid is at once vaporised, and the mercury is observed to sink. The small conical cup is again filled up, and the resulting vapour makes the mercury sink farther. The same process is repeated till it is observed that any small quantity of the liquid remains unevaporated in the flask. This point being attained, it is inferred that evapora-

tion has ceased, and that the empty space A is *saturated* with vapour. The vapour in such a case has its *maximum tension* at the particular temperature in which the experiment is performed. If now the flask be subjected to an increase of temperature, evaporation again sets in, till, as before, any liquid is observed at the bottom, when under the new temperature, it is inferred that the space has again become saturated. This proves, therefore, that increase of temperature causes increase in the evaporation, and that the point of *saturation* also rises with the temperature.

If the experiment be performed with the flask full of air, instead of empty, it is found that similar results ensue, with the important difference, however, that more time is required for the point of saturation to be reached in the former case than in the latter, and that time is the longer the denser the contained gas. Evaporation, therefore, takes place more freely in a vacuum than in any space containing air or gas.

Regnault obtained the following results, amongst others, in regard to the tensions of aqueous vapour at different temperatures:—

Temperatures. (Centigrade.)	Maximum Tensions. (Millimetres of Mercury.)
0°	4·60
10°	9·17
20°	17·39
30°	31·55
40°	54·91
60°	148·70
80°	354·64
	Tensions in Atmospheres.
100°	1 (=760 mill.)
121°	2·025
144°	4
180°	9·929
225°	25·125
239°	27·534

It will be seen, from this table, that the tensions increase very rapidly with the temperature, and particularly so at *high* temperatures. Thus, whilst the temperature varies from 100° to 144°, the tension varies from 1 to 4 atmospheres, and whilst the temperature varies from 180° to 225°, the temperature varies (the increase in temperature being nearly the same, viz. 45°) from about 10 atmospheres to $25\frac{1}{8}$.

225. The Hygrometer.—This instrument, as its name implies, is intended to indicate or measure the quantity of aqueous vapour in the atmosphere. There are several forms of it. One in very general use is represented in fig. 178.

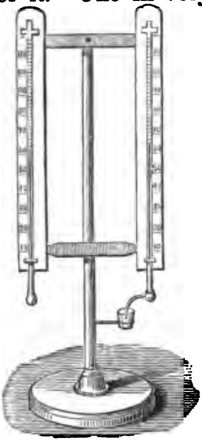


Fig. 178.—THE HYGROMETER.

It is known as the "wet and dry bulb" arrangement. Two thermometers, graduated alike, are attached to a brass stand. The bulb of the one is kept free, whilst that of the other is covered with thin muslin, from which trail a few threads of lamp cotton; these are passed through an aperture in the cover of a small cup containing water, and by capillary action keep the muslin always moist. Owing to evaporation from the wet bulb, and the consequent abstraction of heat from the mercury (see Art. 242), the right hand thermometer shows a *lower* temperature than the other; the greater the evaporation, in other words, the farther removed the air is from its point of saturation, the greater the difference between the readings of the two thermometers. If, therefore, this difference be considerable, it indicates that there is a large quantity of aqueous vapour; on the other hand, if the difference is small, that there is comparatively a small quantity.

This instrument may, so far, also serve the purpose of a barometer. If the difference between the readings be observed to increase, for example, it affords an indication of fine weather; but if this difference decrease, rain may be anticipated.

226. Air Heated by Compression and Chilled by Expansion.—When air is compressed heat is evolved. This can be shown by taking a brass cylinder with a piston fitting it air-tight (fig. 179). In a small aperture at the end of the piston-rod is inserted a piece of tinder. If now the piston be forced down into the cylinder, the air inside becomes compressed, and sufficient heat is evolved to kindle the tinder.

An instrument of this kind has been long in use among some of the native tribes of India.

Again, when air is rarefied or expanded, cold is produced. A striking proof of this is afforded when a receiver is being exhausted by an air-pump. After one or two strokes a *cloudy* appearance is observed in the receiver, resulting from the condensation of the suspended vapour in consequence of the air being chilled.

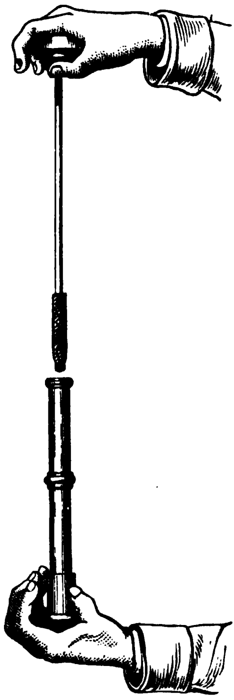


Fig. 179.—HEAT CAUSED BY COMPRESSION.

227. Clouds—Rain.—If a heated mass of air, charged with aqueous vapour, be carried aloft, it will expand by reason of the diminished pressure upon it, and become chilled. It can no longer, therefore, hold all its vapour in suspension; condensation sets in, and that the more rapidly as it ascends, hence the formation of a cloud. *Clouds*, therefore, are masses of aqueous vapour in a partially condensed state. They are not so high as they appear. The greater number of clouds we see are within a few thousand feet of the earth's surface. Hence a mountain traveller often becomes enveloped in clouds, or, if he has attained a considerable elevation, he may witness some clouds floating below him. The motion of clouds is not so regular as we are apt to suppose; they have not a motion of transference merely, but also one in a *vertical* direction, arising from the continued and variable effects of ascending currents.

If the condensation of the vapour in the atmosphere be not confined to the higher regions, but is spread over the surface of the earth, then there is a *mist* or *fog* formed. Fogs arise, for the most part, from the surfaces of rivers, or lakes, or from the damp ground being *warmer* than the superincumbent air.

Rain is caused by a considerable diminution in temperature, and therefore by a rapid condensation of the aqueous vapour. A cloud is capable of holding its moisture so long as the temperature keeps sufficiently high, but should it be carried by the wind into a cool region, it becomes no longer able to do so; rapid condensation sets in, vesicle unites with vesicle, and rain falls. At first the drops are small, but they gradually increase in size, from their uniting with other vesicles in their descent. The rapidity of the rainfall depends upon the amount of vapour in the cloud, and upon the decrease of temperature to which it is subjected. If these elements are carried out far, then the rainfall will be correspondingly great; hence the heavy rains in thunderstorms.

After a continuance of fine weather, it may have been often observed that though clouds are floating in the sky, and give promise of refreshing rain to the thirsty ground, there is no downfall for several days. The fact is, that rain is actually falling in the upper regions, but in consequence of the air below the clouds being non-saturated, the watery vesicles are evaporated in reaching this region; and it is only after the saturation of this air has taken place, that the vesicles unite in such quantity as to reach the surface of the earth as rain-drops.

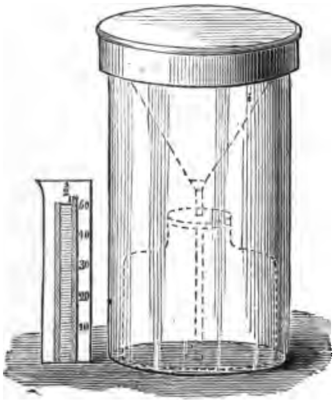


Fig. 180.—RAIN-GUAGE.

228. Rainfall—Rain-guage.—The amount of rain which falls in any district in the course of a year is reckoned by the *number of inches* to which the ground would be covered, supposing the ground perfectly level, and the water neither to sink into the soil, nor evaporate. The *rainfall* is measured by an instrument called "a rain-guage." There are several forms of it. A common form is

represented in fig. 180. A copper cylinder of 5 in. diameter is mounted with a cover having a conical inlet, terminated by a tube which passes into a glass bottle contained inside. This is accompanied by a glass vessel of $\frac{1}{2}$ in. diameter, and 12 in. in height, graduated so as to indicate $\frac{1}{100}$th of an inch of rainfall. After a fall of rain, the bottle is taken out, and the contents are measured by the graduated vessel. The instrument is examined from time to time, and a record is kept of the different quantities obtained in the course of a year. The *mean* annual rainfall of any place, which is usually regarded as the normal fall, is obtained by extending the observations over a series of years. The instrument is generally sunk a little in the ground, so that the top may be at least 6 in. from the surface, and quite horizontal. It is found that a rainguage *near* the surface of the ground always collects more water than when placed in an elevated position. The cause of this is not altogether understood. It seems to be due partly to the increase in size of the drops from the condensation of the vapour as they fall towards the ground from the upper regions. But the chief source of the difference is yet a mystery.

We append a specimen of the rainfalls at different places:

TABLE OF RAINFALLS (AVERAGE ANNUAL).

Names.	Inches.	Names.	Inches.
London (Greenwich),	24·2	Marseilles,	20·3
Manchester,	35·5	Madrid,	15·1
Edinburgh,	25·8	Lisbon,	27·5
Glasgow,	43·2	Milan,	39·8
Glencroe,	127·7	Rome,	31·5
Aberdeen,	27·8	Athens,	15·1
Dublin,	27·7	Jerusalem,	18·5
Cork,	35·5	Alexandria,	10·1
Copenhagen,	23·3	Calcutta,	66·0
Brussels,	28·1	Bombay,	76·2
Paris,	19·9	Madras,	56·3
Pau,	46·8	Melbourne,	25·7

The most remarkable rainfall in the world occurs at Cherrapoonjee, in the Khasyah Mountains; the average is 499·3 in. At Akyab, on the Arracan coast, the famous rice district, the average is 204 in., nearly half this quantity falling in the course of two months. The greatest rainfall in this country

is found at Seathwaite, in the English lake district; its average is 145·1 in. The *least* rainfall in the world of which we have any record is at Suez, 1·3 in.

229. Dew—Dew-point—Hoar-frost.—The phenomenon of *dew* affords a vivid demonstration of the constant presence of aqueous vapour in the atmosphere. It is easy of explanation. After sunset the different objects on the earth's surface begin to radiate or part with the heat which they have absorbed during the day; as the night advances this radiation proceeds, until at length they acquire a much lower temperature than the air above them. The consequence is that the air gets chilled *below* the point at which it can hold its vapour in suspension, condensation ensues, and a deposition of moisture or dew takes place. The point at which the deposition begins is termed the *dew-point.* The amount of this deposition on the different objects depends upon their radiating powers. Thus dew is found to form copiously on grass, the leaves of flowers or trees, and on other products of vegetation, because these are good radiators of heat; whilst, again, the supply is small on stones or the naked soil, because their radiating power is feeble.

It is only, however, in certain states of the atmosphere that dew is deposited. Cloudy or windy nights are unfavourable to its production. In the former case, though there is radiation going on from the earth's surface, yet the clouds are also good radiators, and they thus prevent the surface from being cooled much below the temperature of the atmosphere; in the latter case, the constant transfer of the air from place to place acts as a preventive. Clear still nights, on the other hand, are the most favourable, for then the radiation goes on freely.

Hoar-frost is just dew in a frozen state. The formation of hoar-frost is therefore entirely influenced by the causes affecting the deposition of dew.

230. Snow—Snow-crystals.—When the temperature of the air is below 32° F., the vesicles of vapour become frozen, and in uniting together become heavier than the air, and fall as *snow.* The flakes are sometimes small, at other times large, their size depending upon the amount of moisture and the xtent to which the low temperature prevails. Should the

flakes, in their descent, encounter warm strata of air, a partial fusion takes place, and they fall in a half-melted state, forming *sleet*.

Examined with the microscope, snow presents a very beautiful appearance; it is formed of a number of distinct and transparent crystals of ice, which are observed to be grouped together in a variety of ways. Fig. 181 exhibits some of the different forms of snow-crystals which are found.

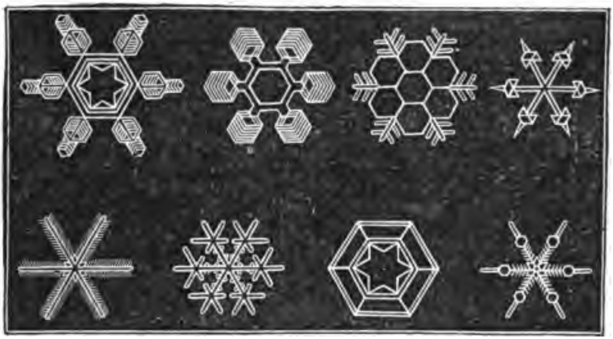


Fig. 181.—SNOW-CRYSTALS.

231. Hail.—*Hail* may be regarded as frozen drops of rain: A small hard nucleus, or centre, is first formed in the upper regions of the atmosphere; this, in its descent, collects more and more moisture on the surface and freezes it, till it at length falls, of some magnitude. Hail rarely falls in winter, chiefly in spring and summer. In winter, from the prevalence of a low temperature, the vapour is condensed and frozen *before* the particles can unite to form drops; hence, in that season, we have snow but not hail. In spring and summer we have often electric discharges, and as these sometimes produce a very sudden cold in the region of the atmosphere where they occur, such discharges are not unusually accompanied by a fall of hail. Hail-storms are often a great scourge to the agriculturist.

CHAPTER VI.

CALORIMETRY—LATENT HEAT.

232. Capacity for Heat.—Bodies differ from each other in regard to their *capacity* for heat; that is, in regard to the quantity of heat required to produce a stated effect, as, for example, to raise them 1° F. or 1° C. In order to measure or compare the capacities of different bodies for heat, it is necessary to adopt some standard or unit. It is customary in this country to adopt as the unit, *the quantity of heat required to raise one pound of water* 1° *C.* at the standard temperature. It is called the *thermal* unit. We infer, therefore, that if a certain quantity of heat raise one pound of water at the standard temperature 1° C., twice that quantity will be required to raise two pounds, three times that quantity three pounds, and so on.

If we take a pound of water at the standard temperature, and one pound of mercury at the same temperature, we find experimentally that the water requires thirty times as much heat to raise it 1° C. as the mercury. The capacity of water for heat is, therefore, said to be thirty times that of mercury.

233. Specific Heat.—By the *specific* heat of a body is meant, *the relation between the quantity of heat required to raise the body, and that required to raise an equal weight of water, through* 1° *C.* at the standard temperature. Thus, referring to the case of mercury mentioned above, the specific heat of mercury will be expressed by the fraction $\frac{1}{30}$ or $\cdot0\dot{3}$. Again, when it is stated that the specific heat of copper is ·095, we mean that the quantity of heat required to raise copper 1° C. at the standard temperature, is $\frac{95}{1000}$, or $\frac{19}{200}$ of that required to raise an *equal* weight of water 1° C., or, which is the same thing, the quantity of heat in the former case is to that in the latter as 19 to 200.

It is of importance to adopt a *particular* temperature in stating the specific heats of bodies, for it is found that these

increase with the temperature. In the case of liquids this variation is more manifest than in solids. With water, however, the increase is found to be *less* than in solids.

234. Method of Measuring the Specific Heat of Bodies.—We mention two methods of measuring specific heat.

(1.) *Method of Mixtures.*—This consists in placing a given quantity of the substance (whose specific heat is required) at a given temperature, in a given quantity of water at a lower temperature, and ascertaining the loss of heat by the former, and the gain by the latter. An example will illustrate the method: Suppose we mix 5 lbs. of a fluid (call it A) at 80° C., with 2 lbs. of water at 10° C., and that the temperature of the mixture is 25° C.; denote by x the specific heat of the fluid. We have here a *decrease* of temperature in A of 55°, and an *increase* in the water of 15°. Therefore the amount of heat given out by 5 lbs. of A will be expressed by $5 \times 55 \times x$; whilst the amount of heat absorbed by the 2 lbs. of water will be expressed by $2 \times 15 \times 1$. Then, since the loss of heat in the one case is just equal to the gain in the other, we have $5 \times 55 \times x = 2 \times 15$, and $x = \frac{2 \times 15}{5 \times 55} = \cdot 109$ nearly; hence the specific heat of A $= \cdot 109$.

This method, though termed the method of mixtures, is applicable also to the case of a solid. Thus let 2 lbs. of a solid (S) at 100°C. be immersed in 3 lbs. of water at 20° C., and suppose the water to rise to 30°; calling x, as before, the specific heat required, then we have the equation $2 \times 70 \times x = 3 \times 10 \times 1$, hence x, or the specific heat of S $= \frac{3}{14} = \cdot 214$.

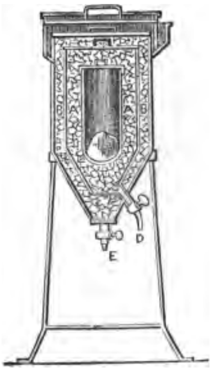


Fig. 182.—Ice Calorimeter.

(2.) *The Ice Calorimeter.* — This instrument was invented by the French philosophers, Lavoisier and Laplace. A sectional drawing of it is shown in fig. 182. It consists of three tin vessels, one within the other, the spaces A, B, between being filled up with pounded ice at 0° C. The body, whose specific heat is to be determined, is

placed in the central one. There are two stop-cocks E, D, for running off the water caused by the fusion of the ice on the part of the surrounding atmosphere and the heated body, respectively. In order to use it, the body of weight W, suppose, being raised to a given temperature t, is quickly placed in the central vessel, and allowed to remain there till its temperature sinks to 0°C. The water resulting from the fusion of the ice is then drawn off at the stop-cock D and weighed. Let this weight be w. Now, as it requires 80°C. of heat to convert a pound of ice at 0° C. into water at 0° C. (see Art. 240), the quantity of heat absorbed by the collected water will be expressed by $80 \times w$; whilst the quantity of heat given out by the body will be expressed by $W \times t \times x$, where x, as before, is the specific heat required. We have therefore the equation, $W \times t \times x = 80w$; hence $x = \frac{80\,w}{W\,t}$.

A certain amount of error results in the use of this instrument, from the fact that all the water does not escape; part of it adheres to the ice in its half-melted state.

235. Table of Specific Heats.—The following table gives the specific heats of certain bodies, as determined by Regnault:—

MEAN SPECIFIC HEATS (BETWEEN 0°C. AND 100°C).

Water,	1·0050	Copper,	·0951
Mercury,	·0333	Silver,	·0570
Wood charcoal,	·2411	Tin,	·0562
Sulphur,	·2026	Gold,	·0324
Iron,	·1138	Platinum,	·0324
Zinc,	·0955	Lead,	·0314

Of all substances, *water* possesses the greatest capacity for heat, and therefore also parts with the greatest amount of heat when cooled down through a given range of temperature. This property is largely utilised in practice, as, for example, in the heating of buildings by hot water, and in feet warmers in beds or railway carriages.

The high specific heat of water plays an important part in the economy of nature. The specific heat of air has been found to be nearly 4·2 times *less* than that of water. It follows, therefore, that 1 lb. of water in losing 1° C., would warm 4·2 lbs. of air 1° C. But water is 770 times as heavy

as air; hence, comparing equal volumes, a cubic foot of water in losing 1° C. would raise $770 \times 4{\cdot}2$, or 3234 cubic feet of air 1° C. We see from this, "the great influence which the ocean must exert on the climate of a country. The heat of summer is stored up in the ocean, and slowly given out during the winter. Hence one cause of the absence of extremes in an island climate."*

236. Experimental Illustration.—The difference which subsists between bodies, in regard to their capacity for heat, may be strikingly shown by the following experiment:—A cake of bees'-wax is placed upon the ring of a chemical stand (fig. 183). Three balls of different metals—iron, copper, lead—are immersed in a bath of very hot oil till they all acquire its temperature. If now they be taken out and put upon the cake, they make their way through at different rates—the iron ball first, the copper next, and last of all the lead.

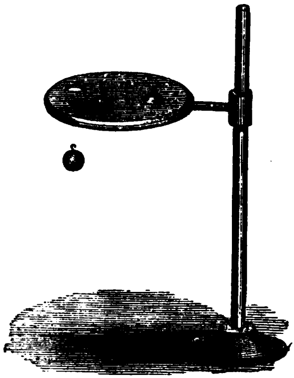


Fig. 183.

237. Specific Heat of Gases.—In regard to gases, there are two kinds of specific heat distinguished, viz.—

(1.) *Specific Heat at Constant Pressure.*—This is the quantity of heat required to raise a given weight of the gas, as compared with an equal weight of water, through 1° C., supposing the pressure on the envelope containing the gas to remain *constant* during the process; and

(2.) *Specific Heat at Constant Volume.*—The quantity of heat required to produce the same effect, as compared with an equal weight of water, when the containing vessel is rigid or the volume of the gas is kept constant.

It can be readily imagined that the former is greater than the latter, because of the absorption of an additional amount of heat due to the expansion. The relation between the two specific heats is estimated at 1·414 : 1.

* Tyndall on *Heat as a Mode of Motion*, p. 143.

It is to Regnault we owe the most complete investigation of the specific heats of gases. The following table exhibits some of his results:—

SPECIFIC HEATS OF GASES (AT CONSTANT PRESSURE).

Air, ...	·2374	Chlorine, ...	·1210
Oxygen, ...	·2175	Carbonic acid, ...	·2163
Nitrogen, ...	·2438	Olefiant gas, ...	·4040
Hydrogen, ...	3·4090	Ammonia, ...	·5083

238. Problems on Specific Heat.—The student is recommended to note the following questions and the method of solution:—

EXAMPLE I.—A pound of lead at 50° C. is immersed in a pound of water at 0° C.; what will be the resulting temperature of both? (1872.)

Supposing the capacity for heat of both the lead and water to be *alike*, it is clear that the common temperature would be 25° C. But the specific heat of lead is only ·0314, hence the 50° of temperature must be divided between the lead and water in the proportion of 314 : 10,000 = 157 : 5000. We have therefore to state thus—

$$5157 : 157 :: 50 : x; \text{ hence } x = 1\cdot52°. \textit{ Ans.}$$

EXAMPLE II.—A pound of cold iron is placed in a pound of water at 200° F. The water loses 5° of temperature. How much has the iron gained in temperature? (May Examination, 1871.)

The water *loses* 5° F. or $2\frac{7}{9}$° C. Now the specific heat of iron being ·1138, the water in being cooled down $2\frac{7}{9}$°, must give out to the iron a quantity of heat $= 2\frac{7}{9} \times \frac{10000}{1138} = 2\frac{7}{9} \times 9$ (nearly) $= 25$; hence the iron has gained in temperature 25° C. or 45° F. *Ans:*

EXAMPLE III.—A cubic foot of water at 70° F. is placed in contact with 100 cubic feet of air at 50°; the water sinks to 69°; supposing all the heat that the water has lost communicated to the air, what would be the exaltation of the temperature of the air (given the specific heat of air = ·25, and its specific gravity $\frac{1}{770}$)? (1869.)

The cubic foot of water in losing 1° C. would warm 4×770 cubic feet of air 1° C.; therefore, in losing 1° F., it would warm $\frac{5}{9} \times 4 \times 770$ cubic feet 1° C., or, which is the same thing, 1 cubic foot $\frac{5}{9} \times 4 \times 770$ degrees centigrade. Hence 100 cubic feet would be warmed $\frac{5}{9} \times 4 \times 7\cdot7$ degrees, and $100 : \frac{5}{9} \times 4 \times 7\cdot7 :: 180 = 30\cdot8°$ F. *Ans.*

239. Latent Heat.—During the passage of a body from the solid to the liquid state, or from the liquid to the gaseous state, its temperature remains *constant*, whatever be the intensity of the heating source. The heat which the body receives in its *transition state* does not affect the thermo-

meter, does not manifest itself, and on this account it is called "latent." We may define *latent heat*, therefore, as *the quantity of heat which disappears or is lost to thermometric measurement, when the molecular constitution of a body is being changed.*

Thus if we take a block of ice, say at − 10° C., and apply heat to it, its temperature rises till it comes up to 0° C. At this point the temperature remains stationary until the last particle of ice is melted. When this takes place, the temperature again rises till it reaches 100° C., when it once more remains stationary, the water then gradually passing off in the form of steam.

240. Latent Heat of Water and Steam—(1.) *Water.*—If 1 lb. of water at 80° C. be mixed with 1 lb. of water at 0°, the temperature of the mixture is 40° C. But if 1 lb. of water at 80° C. be mixed with 1 lb. of pounded ice at 0°, there will result 2 lbs. of water at 0° C. It follows, therefore, that 1 lb. of ice at 0° C., in being changed into 1 lb. of water at 0° C., requires as much heat as would raise 1 lb. of water through 80° C., or, which is the same thing, as would raise 80 lbs. of water 1° C. Consequently, the number 80° C. (144° F.) expresses the latent heat of water or of the fusion of ice.

(2.) *Steam.*—The latent heat of steam may be determined by observing the time required to raise a given quantity of water through a certain number of degrees, and then comparing this with the time between the commencement of boiling and the total evaporation of the water. It has been estimated at 540° C. (967° F.), implying that during the conversion of 1 lb. of water at 100° C. into 1 lb. of steam at the same temperature, as much heat is imparted as would raise 540 lbs. of water 1° C.

The latent heat of steam is of service in cookery. Vegetables and meat are often cooked by allowing the steam from boiling water to pass through them; in doing so, the steam becomes condensed and parts with its latent heat. We can easily understand from this the severity of a scald from steam.

241. Problems on Latent Heat.—A series of interesting problems on latent heat may be solved by attending to the principles just laid down. The following examples are worthy of the student's notice;—

EXAMPLE I.—How many lbs. of steam at 100° C. will just melt 100 lbs. of ice at 0° C.?

Let x be the number of lbs. The number of units of heat given out by x lbs. of steam when reduced to water at $100° = 540\,x$; but, further, the x lbs. of water in falling to 0° give out an additional number of units, viz., $100\,x$.

Again, the 100 lbs. of ice require 100×80 units to convert it into water, and as the number of units given out by the steam must equal that absorbed by the ice, we have, therefore, the equation

$$540\,x + 100\,x = 100 \times 80, \text{ whence } x = 12\tfrac{1}{2} \text{ lbs. } \textit{Ans.}$$

EXAMPLE II.—How many lbs. of steam at 100° C. would raise a gallon of water from 0° C. to 90° C.? (1 gallon of water = 10 lbs.)

Let x be the number. The number of units of heat given out by the steam to reduce it to water at 90° C. $= 540\,x + 10\,x$; hence we have

$$540\,x + 10\,x = 10 \times 90, \text{ and } x = 1\tfrac{8}{11} \text{ lbs. } \textit{Ans.}$$

EXAMPLE III.—If 1 lb. of steam at 100° C. be mixed with 49 lbs. of water at 15° C., what will be the temperature of the 50 lbs. of water?

Let x = temperature. Here the number of units of heat given out by the steam to reduce it to water at the required temperature $= 540 + (100 - x)$; hence we have

$$540 + (100 - x) = 49\,(x - 15), \text{ and } x = 27\tfrac{1}{2}°. \textit{ Ans.}$$

EXAMPLE IV.—An ounce of steam at a temperature of 212° F. is added to a pound of water at a temperature of 50°; what will be the temperature of the mixture? (May Examination, 1869.)

Let x = temperature. The number of units given out by the steam $= \frac{1}{16} \times 967 + \frac{1}{16}\,(212 - x)$; hence we have

$$\tfrac{1}{16} \times 967 + \tfrac{1}{16}\,(212 - x) = 1 \times (x - 50), \text{ and } x = 116\tfrac{7}{17}° \text{ F. } \textit{Ans.}$$

COLD PRODUCED BY EVAPORATION—FREEZING MIXTURES.

242. Cold of Evaporation.—In the passage of water or any other liquid into vapour, there is a quantity of heat rendered latent. This heat is chiefly derived from the liquid itself, hence the temperature of the liquid is lowered. We have therefore the important fact that *cold is produced by evaporation.* The more rapidly evaporation proceeds, the degree of cold is the greater. If, for example, we take the three liquids, water, alcohol, and sulphuric ether, and put a drop of each successively on the hand, then waving the hand backwards and forwards in the air to hasten the evaporation, we find that the sensation of cold is least with the water, greater with the alcohol, and still greater with the

ether. This arises from the rate of evaporation at the same temperature being different in the three liquids.

243. Freezing by Evaporation.—Evaporation may proceed so rapidly as to cause refrigeration. This may be effected in the following manner:—A small capsule containing water is placed in a flat dish filled with sulphuric acid. The whole is placed under the receiver of an air-pump, and the air exhausted. As the rarefaction proceeds the water evaporates, the vapour being immediately absorbed by the sulphuric acid, till the remaining water begins to freeze, and eventually becomes a solid lump. This experiment is due to Leslie.

Another experiment consists in filling a test tube with water, surrounding it with cotton wool saturated with sulphuric ether, and blowing a stream of air upon it by means of a pair of bellows (fig. 184). The evaporation of the ether takes place rapidly, and the water in a short time becomes frozen.

Fig. 184.—Freezing by Evaporation of Ether.

The method often followed out in India of procuring ice, affords an illustration of the same thing.

Early in the cold weather, when the nights are clear, shallow unglazed earthenware pans filled with water are put

out in the open air. Evaporation rapidly takes place, and during the process, when the temperature of the water falls below the freezing point, a thin stratum of ice forms on the surface. Before daybreak the thin cakes of ice are removed from the pans, and the accumulated mass, well hammered together, is stowed away in the ice-house.

Water coolers, so much used in summer, owe their action to the same principle.

A remarkable instance of freezing by evaporation occurs in a grotto near Vergy in France. In some places columns of ice appear to support the vault of the grotto; at others they are seen hanging from the roof, or resting upon the ground. The water passes slowly in traversing the vault, and its evaporation hastened by currents of air produces the ice. It is not in winter alone that this take place, nor can the formation of the "*glacières naturelles*" be attributed to a cooling down of the air.

Fig. 185.—The Cryophorus.

244. The Cryophorus.—This instrument, invented by Wollaston, is founded on the same principle. It is represented in fig. 185. It consists of two glass bulbs, A and B, connected by a tube. Water is put in the bulb A, and whilst a small orifice is left open at the bottom of the bulb B, the water is boiled; the steam escaping from the water chases out the air, and when this is all expelled, the orifice is closed by means of a blowpipe. On the water regaining its ordinary temperature, there is left in the apparatus nothing but a little water and its vapour. If now the bulb A be placed in a vessel to get rid of currents of air, whilst the other bulb B is plunged into a freezing mixture, such as snow and salt, the

vapour as it escapes from the water is condensed, and in the course of half an hour or so the water in A begins to freeze.

245. Freezing of Mercury by Evaporation.—The cold produced by evaporation may be made such as even to freeze mercury, the freezing point of which is as low as $-39°$ C.

To effect this a test tube is taken with a small quantity of mercury in it (fig. 186). Over the mercury is poured some sulphurous acid—a liquid even more volatile than ether. The top is closed with an india-rubber stopper, through which two glass tubes pass. One of these reaches to the bottom of the acid, and is connected with a bladder full of air, whilst the other is kept free. The bladder being compressed, the air is forced through the sulphurous acid, its evaporation is thereby hastened, and after a little time the mercury is frozen.

Fig. 186.—Freezing by Evaporation of Sulphurous Acid.

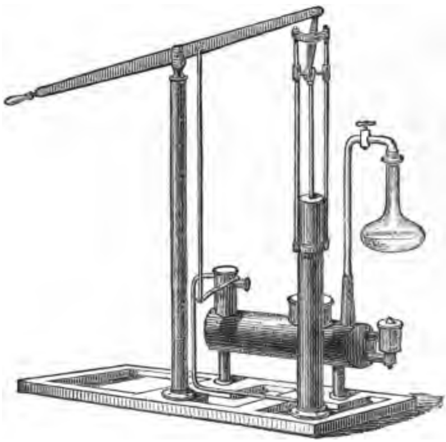


Fig. 187.—Carre's Freezing Apparatus.

246. New Ice-Making Machines.—Carré, of Paris, some

years ago invented a machine for the making of ice, founded on the principle of cold produced by evaporation. The apparatus is shown in fig. 187. It consists of an air-pump of peculiar construction, in the body of which is placed sulphuric acid. This is put in connection with a glass vessel containing the water. The end of the connecting tube terminates in a hollow india-rubber plug, which fits into the neck of the bottle. When the pump is worked the rarefaction proceeds, and at the same time rapid evaporation takes place from the surface of the water. The vapour as it escapes into the body of the pump is absorbed by the sulphuric acid, and as the process continues the temperature of the water becomes reduced below the freezing point, when almost immediately the whole water becomes solidified. The apparatus is so speedy in its action that a few minutes only are necessary to produce the effect.

Pictet, of Geneva, has recently invented a machine for the manufacture of ice in large quantities. He adopts sulphurous acid as the volatile liquid. By this machine 250 kilogrammes of ice (5 cwt. nearly) can be made per hour with an engine of seven horse-power applied to work it. The cost of production is stated to be 10 francs per ton.

247. Freezing Mixtures.—We have seen that during the process of liquefaction a quantity of heat is rendered latent. If a body is liquefied otherwise than from some external source, then, as heat is necessary to produce the liquefaction, this heat must be derived from the bodies in contact with it, and consequently a diminution in temperature must take place.

"The absorption of heat which accompanies the liquefaction of solids is the basis of the action of freezing mixtures. In all such mixtures there is, at least, one solid ingredient which, by the action of the rest, is reduced to the liquid state, thus occasioning a fall of temperature proportional to the latent heat of its liquefaction.

The mixture most commonly employed in the laboratory is one of snow and salt, in the proportion of two parts of the former to one of the latter. This mixture assumes a temperature of about $-18°$ C. ($0°$ F.), and furnished Fahrenheit with the zero of his scale. In this instance there is a double

absorption of heat caused by the simultaneous melting of the snow and dissolving of the salt."*

We append a table of some of the more common freezing mixtures:—

TABLE OF FREEZING MIXTURES.

	Proportions by Weight.	Cold Produced.
Snow or pounded Ice,	2	−18° C.
Commom Salt,	1	
Snow,	3	−48° ,,
Crystallised Chloride of Calcium,	4	
Water,	1	−15° ,,
Nitrate of Ammonia,	1	
Sulphate of Soda,	8	−17° ,,
Hydrochloric Acid,	5	

The last of these mixtures is largely used by confectioners.

* Deschanel, p. 305.

CHAPTER VII.

CONVECTION—CONDUCTION—COMBUSTION.

248. Convection of Heat.—By the *convection* of heat is meant that process by which heat is *carried* and distributed through the mass of a fluid body by the actual motion of its own particles. Thus, water is boiled by convection. When heat is applied to a vessel of water, as in fig. 188, there are produced a series of ascending currents which carry the heat to the other parts of the liquid, until the water is raised to the boiling point.

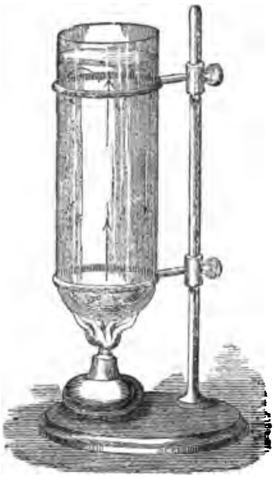


Fig. 188.—CONVECTION CURRENTS.

The currents may be exhibited by throwing into the liquid a little roughly-powdered amber, or common sawdust. A more striking experiment is to introduce carefully into the vessel, before the heat is applied, a strong solution of indigo, by means of a burette. The solution, from its density, remains at the bottom, and when the flame is applied, the dark fluid is seen to course upwards and downwards with the ascent and descent of the current, producing a very pretty effect.

Winds are evidently just convection currents.

249. Applications of Convection.—The principle of convection is taken advantage of in practice to a large extent.

It is owing to convection that hot water is carried and distributed through different parts of a dwelling of modern construction. A high pressure boiler, in connection with the cistern of the house, is fitted behind the kitchen fire, and pipes are led from this to the parts of the house to be supplied, returning again to the boiler. The warm water, aided by the elastic force of the steam, ascends the pipes, and may be drawn off at pleasure, whilst the surplus, becoming cool by radiation and contact with the pipes, returns to the boiler and gets an additional supply of heat. Thus a constant circulation is maintained.* A similar plan is often carried out in the heating of greenhouses. So also in the heating of public buildings, arrangements are adopted for maintaining a constant circulation of hot water through the pipes led into the different apartments.

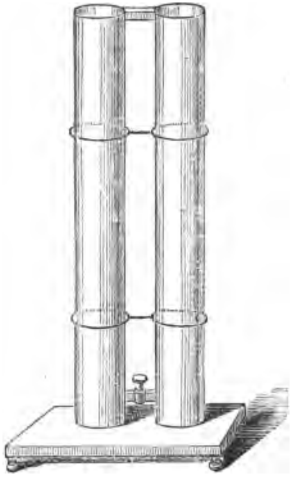


Fig. 189.—JOULE'S APPARATUS.

250. Determination of the Maximum Density of Water. — The maximum density of water was determined by Joule in the following ingenious way: He took two glass vessels, each $4\frac{1}{2}$ ft. high, and 6 in. diameter (fig. 189), and connected them at the bottom by a tube provided with a stop-cock, and at the top by an open channel. The stop-cock being closed, water of different temperatures was poured into the tubes to such

* In the event of the accumulation of steam becoming such as to endanger the boiler, the precaution is adopted of leading a pipe directly from the boiler to the outside of the house. When the accumulation becomes dangerous, the water is expelled through this pipe, and thus the boiler is relieved from any pressure *which would be apt to cause* rupture.

a level as to flow freely through the channel. In this conduit he placed a small floating bead. The temperatures of the water being noted, the stop-cock was then opened, and a convection current flowed between the two vessels, as shown by the motion of the bead. Noticing the *direction* of the bead's motion, and adjusting the temperatures of the water, he found, by successive experiments, a pair of temperatures which arrested all motion on the part of the bead, or which produced no convection currents. This, of course, indicated that the one temperature which he had obtained was as much *above* the maximum density as the other was *below* it. By finding a series of pairs of temperatures which gave the same result, he brought down the difference to be smaller and smaller, and eventually determined the maximum density to be at 39·1° F.

251. Conduction of Heat.—Heat is said to be conducted, or diffused by *conduction*, when it passes from molecule to molecule of a body.

"When the end of a poker is thrust into the fire it is heated; the molecules in contact with the fire are thrown into a state of more intense oscillation; the swinging atoms strike their neighbours, these again theirs, and thus the molecular music rings along the bar. The motion, in this instance, is communicated from atom to atom of the poker, and finally appears at its most distant end. . . .

"This molecular transfer, which consists in each *atom* taking up the motion of its neighbours, and sending it to others, is called the *conduction* of heat." *

Bodies differ much from each other as regards their conducting power, or *conductivity*, as it is more generally called. Thus, metals as a class are the best conductors, though differing greatly from each other; whilst such bodies as wood, glass, wool, cotton, etc., are very imperfect conductors.

All liquids and gases possess a very feeble conducting power. If, for example, a vessel of water be heated *from the top* by pouring gently on the surface a quantity of boiling oil, it is found that the heat makes its way downwards with extreme slowness, and it is only after a considerable time

* Tyndall on *Heat as a Mode of Motion*, p. 191.

that the least rise in temperature is observable at the bottom of the vessel.

Snow is a very imperfect conductor of heat. Travellers, when overtaken by a snow-storm, in some instances have had their lives preserved by taking shelter in a wreath of snow, before being benumbed by the cold. So also sheep have been taken out alive, though buried amidst snow for some time.

The Esquimaux, it is said, construct their winter huts of snow. They shape the snow into large hard masses, which they place upon each other as our masons do stones; they then pour into the crevices ice-cold water, which upon freezing unites the whole into one solid mass. The inside being covered with the skins of animals, a comfortable dwelling is thus provided.

This quality of snow is not without its use in the general economy of nature. In severe climates, it prevents the earth from being so much cooled down as to endanger those germs of vegetation which await the return of spring.

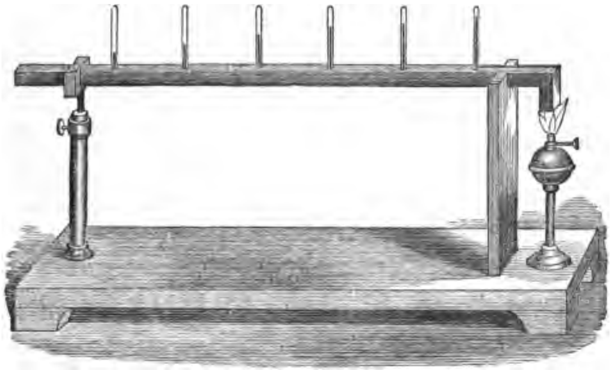


Fig. 190.—CONDUCTIVITY OF METALS.

252. Determination of Conductivity in Solids.—Several methods have been proposed with a view to determine the conductivities of different substances. The method most commonly carried out, and probably the most accurate, is that suggested by Fourier. It consists in observing the *permanent distribution* of temperature in a bar of uniform

width and thickness, having one of its ends exposed to a steady source of heat. Along the bar are drilled a series of holes (fig. 190), for the reception of the bulbs of so many thermometers. When the heating source is applied, the different thermometers begin to rise, and at rates dependent upon the material of the bar; but after a stated time, owing to the effects of radiation and convection from the cool surrounding air, they all maintain a steady temperature. The readings of the different thermometers are then noted. The same thing is done with bars of different material, that is, the times required for the *steady* indications of the thermometers, and the readings after those times are carefully noted. From these data the conductivities are determined. By this method, but using instead of thermometers a modification of the thermo-electric pile, Wiedemann and Franz drew out the following table:—

CONDUCTIVITIES OF METALS.

Silver,	100	Iron,	12
Copper,	74	Lead,	9
Gold,	53	Platinum,	8
Brass,	24	German silver,	6
Tin,	15	Bismuth,	2

It has been found that the numbers in the above table nearly express the conductivities of the different metals, also, for electricity. Forbes was the first to remark this; he further proved, experimentally, that the thermal conductivity of iron *diminishes* as the temperature rises.

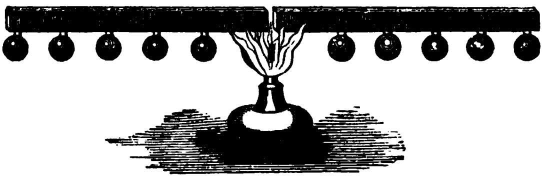


Fig. 191.—Relative Conductivity of Brass and Iron.

253. Experimental Illustrations.—The difference in the conductivity of metals may be illustrated by the following experiments:—

(1.) Two bars of different metals, such as copper and iron, are placed as in fig. 191. At equal distances along the bars are attached a series of wooden balls by means of wax. When the ends are heated by a lamp, the heat is propagated along the bars, but as the copper is a better conductor than the iron, the wax on the former is more readily melted, and a greater number of balls fall off from the copper than from the iron in the same time.

(2.) Two spoons, one of silver and the other of German silver, are placed on a tripod, in a beaker of hot water (fig. 192). A piece of phosphorus is put at the end of each. In a short time sufficient heat is conducted along the silver spoon to inflame the phosphorus, whilst that upon the other spoon remains unaffected.

Fig. 192.

254. Effect of Mechanical Texture.—Mechanical texture has an effect on the conduction of heat. Thus, twisted silk conducts heat more readily than raw silk; hard rock crystal more readily than when reduced to powder; wood more readily than in the state of sawdust. The reason is, that in the latter cases the molecular chain is not so continuous; it is broken up by air-spaces.

255. Clothing.—As the object of clothing is to prevent the escape of heat from the body, we must of course select those substances as articles of dress which offer resistance to the passage of heat, or such as are bad conductors. The common notion that there is natural warmth in any material is quite a wrong one. There is really no more natural heat in a piece of flannel than there is in a piece of lead. Flannel is an excellent covering for a man in winter; it is nevertheless also the best substance for wrapping round ice to prevent it melting in summer. In the former case the source of heat being within, the flannel prevents the escape of heat, and

thus contributes largely to warmth; in the latter case, the source of heat is from without, and the flannel being a bad conductor effectually prevents the passage of heat into the ice.

There being therefore no such thing as natural warmth in any material, it is evident that the lower the temperature to which we are exposed, the greater the waste of animal heat would be; hence in cold weather it becomes necessary to surround the body with such materials as are the worst conductors of heat. Now, according to experiment, fur is the worst conductor, and therefore the warmest covering; next to it is wool, fabricated into the different textures of flannel and cloth; next are cotton, linen, and silk, which being better conductors, form therefore a comparatively cool covering, and are fit only for the higher temperatures of summer.

Air is a bad conductor of heat; hence loose clothing is warmer than we are apt to imagine.

256. Sensations of Heat and Cold.—The different sensations of heat and cold, which we continually experience in *touching* bodies, arise altogether from conduction. When two bodies of different temperatures are placed in contact, the warmer parts with its heat to the colder, until they both acquire the same temperature. There is a constant tendency towards an *equilibrium of temperature.* Suppose, then, that a person in a room without a fire were to touch first the carpet, then the table, then the wall, and lastly the fender, he would consider each of them colder and colder in succession. Why? The reason is simply this: the carpet being a bad conductor, carries little heat off from the hand; the table is a better conductor, and thus feels colder; the wall is a better conductor still, and therefore feels still colder; but the fender is the best conductor of the whole, and accordingly it carries off the heat rapidly, giving thereby the most powerful sensation.

257. Combustion.—Combustion, such as we have it in our coal, in our gas and candle flames, is due to the chemical union of the oxygen of the air with the substances present in these.

Coal-gas is a chemical combination of carbon and hydrogen. When the jet of escaping gas is ignited, "the oxygen of the air unites with the hydrogen, and sets the carbon free. In-

numerable solid particles of carbon thus scattered in the midst of the burning hydrogen, are raised to a state of intense incandescence: they become white-hot, and mainly to them the *light* of our lamps is due. The carbon, however, in due time, closes with the oxygen, and becomes, or ought to become, carbonic acid; but in passing from the hydrogen, with which it was first combined, to the oxygen with which it enters into final union, it exists for a time in the solid state, and then gives us the splendour of its light." Within the flame there is a core of unburnt gas.

"The combustion of a *candle* is the same in principle as that of a jet of gas. On igniting the wick, it burns, melts the tallow at its base, the liquid ascends through the wick by capillary attraction, it is converted by the heat into vapour, and this vapour is a hydro-carbon, which burns exactly like the gas." *

258. Structure of a Candle Flame.—It is to Sir Humphry Davy that we owe our knowledge of the precise theory and constitution of flame. The structure of a candle flame will be understood from fig. 193. It consists of three parts: (1) the space occupied by the unburnt vapour; (2) the luminous zone or area where the carbon particles are in a white-hot, glowing state; (3) the area of complete combustion, from which the greatest amount of heat is evolved. The presence of unburnt vapour within may be shown by placing a small glass tube, as in the figure. The vapour escapes through the tube, and may be ignited at the other end.

Fig. 193.—STRUCTURE OF CANDLE FLAME.

The same thing may be shown by lowering a piece of white paper upon the flame till it nearly touches the wick. A blackened or charred ring is formed upon the paper, whilst within the ring the paper is unaffected.

259. Experiments with Wire Gauze.—If a piece of fine wire gauze be lowered upon a gas jet, the flame spreads out

* Tyndall on *Heat as a Mode of Motion*, pp. 46, 47.

below (fig. 194), but is unable to penetrate the meshes of the gauze. This is owing to the conduction of the heat by the gauze, in consequence of which the gas that escapes through cannot become ignited. On placing the gauze *close* upon the top of the burner and lighting the gas, the flame may be lifted off by gently raising the gauze, and eventually extinguished.

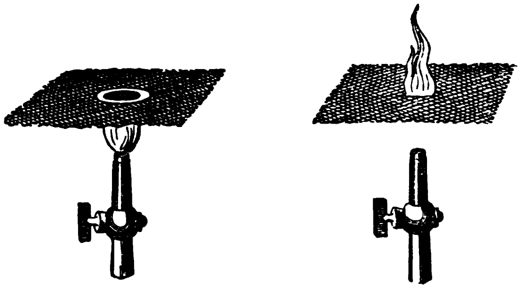


Fig. 194.—Wire-Gauze Experiments.

Another striking experiment is to pour flaming spirits of wine upon a piece of gauze; most of the fluid drops through, leaving the flame burning upon the gauze.

Fig. 195.—Davy Safety-Lamp.

The "Davy Safety Lamp," so much used by miners, is constructed on this principle. It consists of an oil lamp enclosed within a cylinder of gauze (fig. 195).

260. Bunsen Lamp.—The luminosity of flames, as we have seen, is mainly due to the existence of solid carbon particles. Hence when a large quantity of air is allowed to mix with them their combustion is quickened, and heat is developed at the expense of intensity of light. This is what is effected by a *Bunsen lamp*, so much used in chemical and physical laboratories. It is represented in fig. 196. The gas, escaping from a central burner, up the tube, draws with it a quantity of air through the small holes

near the base. The mixture of gas and air is then ignited at the top of the tube, and burns with a feeble light, but evolves considerable heat, owing to the complete combustion of the carbon. If the small holes be closed, the flame assumes its ordinary appearance.

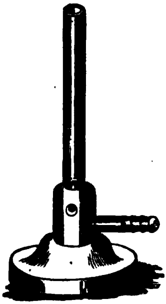


Fig. 196.—Bunsen Lamp.

261. Animal Heat.—The heat of our bodies is due to a slow combustion constantly going on. The oxygen of the air we inspire combines with the carbon elements of the blood and animal tissue, and by their union heat is evolved—the carbonic acid thus formed being constantly exhaled. The air we expire contains from 3 to 6 per cent. of carbonic acid, and will not support the combustion of a candle.

CHAPTER VIII.

RADIATION—ABSORPTION—DIATHERMANCY.

262. Radiation of Heat.—There is no quality so abundantly obvious in reference to heat than its tendency to diffuse itself in all directions from the heating source. This passage of heat through intervening space is called *radiation*, and the heat thus passing *radiant* heat.

Radiation is not dependent upon the presence of air; it takes place also in a vacuum. This is manifest when we consider how it is that we derive heat from the sun; his heating rays require to pass through an intervening void before they reach our earth.

If this be so, the question arises, wherein then does radiation consist? for it is impossible to conceive of the transference of heat from one body to another *without* some channel of communication. The medium of conveyance is the all-pervading ether. The mechanical theory of heat, as we have seen (Art. 179), affirms that the particles of a hot body are in a state of vibration, and the hotter a body is the more rapid is that vibration. The vibrations of the radiating body, therefore, are communicated to the surrounding ether, and are thereby transferred to other bodies in its vicinity. We may accordingly define *radiation* to be in the language of this theory, *the communication of the motion of the particles of a warm body to the surrounding ether, by which that motion is propagated to other bodies.*

263. Prevost's Theory of Exchanges.—We are accustomed to speak of warm bodies only radiating heat; but the fact is that *all* bodies, of whatever temperature, radiate heat. Let us suppose we have two bodies, A and B, of different temperatures, A warmer than B. Radiation not only takes place from A to B, but also from B to A. However, in consequence

of A's excess of temperature, more heat passes from A to B than from B to A, and this continues until both bodies acquire the same temperature.

At this point the radiation does not cease; but now the amount of radiation is the same for both—as much heat passes from B to A as from A to B, or the one body gives out as much heat as it receives from the other. This theory is known as "Prevost's Theory of Exchanges."

264. Obscure and Luminous Radiation.—It is believed, then, that there is no body absolutely cold, that is, none which altogether ceases to radiate heat. So long as a body is kept below a certain temperature, the heat rays emitted by it are incapable of exciting the optic nerve; the radiation in this case is said to consist of *obscure* rays. As the temperature is increased, however, *luminous* radiation sets in, that is, the rays now emitted excite vision, and give rise to the perception of colour.

The gradation from obscure to luminous radiation is well manifested in the following experiment:—A thin platinum wire is traversed by an electric current of gradually increasing strength. The wire, owing to the resistance which it offers to the passage of the current, becomes heated. At first, when the current is weak, the wire is sensibly warm to the hand; but, after a time, it becomes too much heated for the touch. It still, however, emits invisible rays. As the power of the current rises, the wire at length begins to glow, emitting a dull red heat; it then passes through different stages of brilliancy and colour, till eventually it emits a dazzling white light, similar to that of the sun.

Throughout the changes which the platinum wire undergoes, it is worthy of notice that the radiation of the obscure rays is preserved; these rays maintain their individuality to the end, and commingle with the luminous ones.

265. Thermo-Multiplier.—The researches connected with radiant heat, which have been made in modern times, have been prosecuted by the aid of an apparatus known as the "Thermo-Multiplier."

To enable the student to obtain a clear conception of the action of this apparatus, a few remarks on the principles involved in its construction are desirable.

When a bar of antimony A and another of bismuth B are soldered at the ends (fig. 197, *a*), and the point of junction is heated, a current of electricity is generated, flowing in the connecting wires attached to the free extremities, in the direction of the arrow. If the point of junction be *chilled* instead of heated, the current flows in the opposite direction.

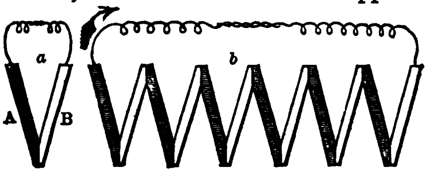


Fig. 197.—THERMO-PILE.

If a series of such pairs be taken and connected as in fig. 197, *b*, the same effects ensue, but the current generated is now much stronger than before. An arrangement of this kind is called a "thermo-electric battery or pile," or, more shortly, a "thermo-pile." It was invented by Nobili. The current generated is made manifest by its effect on a magnetic needle; it deflects the needle from its natural position of rest.

Again, whilst the current remains the same, if the wire conveying the current be insulated and be made to take several convolutions round the needle, each convolution has its own effect, and the combined action of the whole, therefore, is to produce an increased deflection of the needle. Moreover, the deflection of the needle (say the north or marked pole) to the right or left, depends upon the *direction* in which the current circulates in the coils. This is the arrangement carried out in the "multiplying galvanometer."

These principles being premised, the construction and action of the "thermo-multiplier," as improved by Melloni, will now be understood.

A number of pairs of antimony and bismuth are arranged in the form of a square bundle (fig. 198), the alternate bars being joined at their opposite extremities. They are enclosed in a copper casing, and the two ends are furnished with covers which can be removed when the pile is put into action. Two rods provided with binding screws are connected with the *terminal* bars. Wires are led from these rods to a delicate

galvanometer, as in the figure. On exposing either of the open faces to the action of radiant heat, there is generated a current of electricity, whose strength depends upon the number of pairs in the pile, and also upon the difference of temperature at the opposite faces. This current is manifested by a deflection of the needle of the galvanometer; and the stronger the current the greater the deflection. If the face of the pile be exposed to a *chilling* source, such as a block of ice, the current generated flows in the opposite direction, and the needle is deflected accordingly.

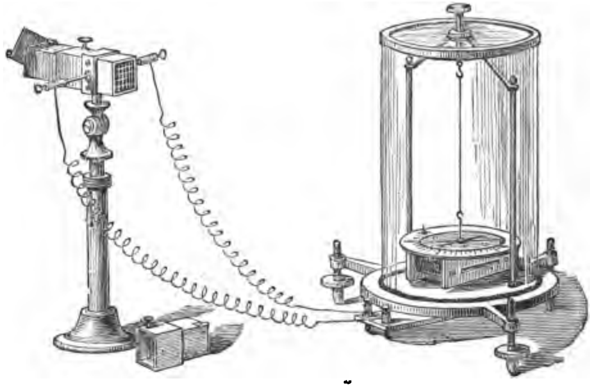


Fig. 198.—THERMO-MULTIPLIER.

This is a very delicate apparatus, and is admirably adapted for investigations into the subject of radiant heat.

266. Radiating Power of Bodies.—Bodies differ much from each other as regards their power of radiation. Sir John Leslie made some interesting investigations on this subject. The apparatus he used consisted of a tin canister in the shape of a cube, the sides of which were covered or coated over with the different substances, whose emissive power were to be determined. The canister being filled with boiling water, the heat given out by the four vertical faces was received upon one of the bulbs of a "differential thermometer,"—an instrument invented by Leslie, consisting of a bent tube partly filled with coloured fluid and terminated at

the extremities by two bulbs. The effects of the expansion of the confined air in the exposed bulb on the position of the fluid being noted, Leslie was enabled to determine the relative radiating powers.

Melloni, subsequently, instituted a number of searching experiments on the same subject. Taking advantage of Leslie's cube or canister apparatus, he disposed this upon a graduated horizontal bar, and maintained the water at the boiling point by placing a spirit lamp below it. At a certain distance along the bar he arranged his thermo-pile, and between he placed two screens, one with an aperture in it directly opposite the face of the pile, and the other entire for the interception of the radiation when necessary. On exposing the separate faces of the cube to the pile, currents were obtained proportional to the radiating powers of the surfaces, and thus by covering the cube with different substances their relative radiating powers could be determined.

The following table gives some of the results of such experiments:—

RADIATING POWERS OF BODIES.

Lamp Black, . . .	100	Platinum, ...	17
Paper, ...	98	Polished Brass, . .	7
Glass, ...	90	Polished Gold, . .	3
Indian Ink, . . .	85	Polished Silver, . .	3

From the above table, it appears that lamp-black possesses the highest radiating power; in fact, it is the best radiator of all known substances. On the other hand, the metals are the worst radiators. The radiation from metals is the worse, the brighter and more polished the surface.

Fire-clay has a high radiating power; hence the common expedient of lining a grate with this substance so as to increase the radiation from the fire.

267. Reflexion of Radiant Heat.—Heat, like light, is capable of reflexion, and follows the same laws (Art. 82). The reflexion of heat is well illustrated by the apparatus represented in fig. 199. Two metallic reflectors mounted on stands are set directly opposite each other. A white-hot iron ball is placed in the principal focus of one of the reflectors; if now a piece of phosphorus be placed in the focus of the other reflector, it bursts into flame, being fired by the heat

emitted from the ball, which has been concentrated by the reflectors at that point.

The reflective powers of substances vary considerably. According to Leslie's experiments the greatest reflexion takes place from bright and polished metallic surfaces. Should the surface be rough or tarnished, the amount of reflexion is much diminished. Glass coated with lamp-black, and white paper, reflect very feebly.

It is said of Archimedes of old, that he set fire to the Roman fleet, during the siege of Syracuse, by means of burning mirrors. Modern experiments have shown that this was quite possible. By the use of large metallic reflectors the sun's rays have been so concentrated as to ignite wood at some distance. Large reflectors have been applied also to the cooking of food by solar heat.

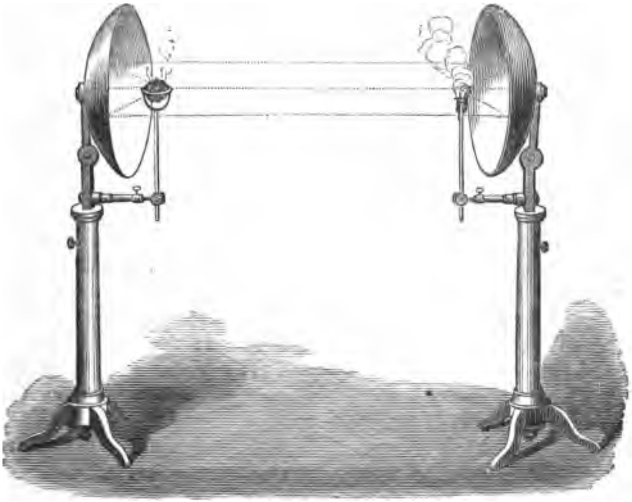


Fig. 199.—Reflexion of Radiant Heat.

268. Application to Common Experience.—We may gather from the foregoing principles many useful and important hints regarding facts of every-day life. Thus we learn why the polished fire-irons, which stand beside a fire, are not

inconveniently heated. The heat which falls upon them is reflected in a great measure by the polished metal. Should they be allowed to become tarnished the reflexion is not so complete, and they become heated. The polish, therefore, of fire-irons is not only ornamental but contributes largely to comfort in handling them. It is of advantage that the interior of a screen placed behind roasting meat be kept clean and polished, for then it is a good reflector, and aids materially the cooking process.

Certain parts of a steam engine ought to be highly polished, not so much for appearance' sake, but as a most effectual means of retaining the heat of the steam, thus preventing loss by condensation. A stove ought to have its exterior surface rough and well blackened, so as to allow radiation to take place freely. A tea-kettle, on the other hand, ought to be well brightened up so as to diminish radiation, and thus tend to retain the heat of the water as long as possible. Should a "cozy" be used for a tea-pot, it ought to be made to fit loosely, for then the radiation is much impeded.

269. Absorption.—The heat which falls upon a body is in part reflected and in part absorbed. The reflected portion, however, in most cases, is not reflected regularly, but is scattered or diffused in every direction from the reflecting surface. The remainder of the incident heat passes into the mass of the body and is said to be *absorbed.*

By the *absorption* of heat, therefore, is meant that quality in a body in virtue of which it receives into its mass more or less of the heat which falls upon it; according to the mechanical theory, we may say that it is the quality manifested in a body of *taking up and appropriating to itself the vibrations of the surrounding ether*, consequent upon the presence of some heating source.

270. Absorbing Power of Bodies.—A marked difference subsists in regard to the powers of absorption of different bodies.

To ascertain the relative absorptive powers of different kinds of cloth, Dr. Franklin made the simple experiment of putting a number of pieces on snow as it lay on the ground. These were exposed for a certain time to the sun's rays, and the depths to which they severally sank in that time were

noted. He found those pieces that were dark in colour sank deepest in the snow, while those that were light-coloured sank least, from which he inferred that the former possessed the greatest power of absorption, and the latter the least. Hence appears the importance of attending to the particular colour of clothing which should be worn in the different seasons. Thus the worst colour of cloth we can wear in winter is black; for, being a powerful radiator, it tends to carry off the heat from the body. In summer, again, a light-coloured dress is the most desirable; for, being a good reflector and a bad absorber, it shields the body from the influence of the sun.

The discovery ships of Captain Parry, it is said, during the severe winter which was spent at Melville Island, were so rigidly frozen in as to render it extremely doubtful whether the influence of the summer's sun would be sufficient to relieve them. To ensure an exit, the method was adopted of strewing ashes and soot in a line from the ships to seaward. The consequence was that these substances, by their great absorption of the sun's rays, dissolved the subjacent ice, thus forming a passage for the ships through the solid ice all around.

In some of the most mountainous districts of Europe, where the snow would lie so long as to retard cultivation, the peasantry have recourse to the plan of strewing a quantity of earth upon the snow; this, by its great absorptive power, assists materially towards clearing the ground.

In regard to gases, some interesting results have been obtained by means of the thermo-pile. The following table gives the relative absorptive powers of certain gases. The gases specified were examined under a pressure of one-thirtieth of the ordinary atmospheric pressure. Taking *unity* as the absorptive power of air, the numbers obtained were as follows:

ABSORPTIVE POWERS OF GASES.

Air,	1	Hydrochloric Acid,	1005
Oxygen,	1	Nitric Oxide,	1590
Nitrogen,	1	Nitrous Oxide,	1860
Hydrogen,	1	Ammonia,	5460
Carbonic Oxide,	750	Olefiant Gas,	6030
Carbonic Acid,	972	Sulphurous Acid,	6480

From the above table it will be observed that the simple gases exhibit extremely little absorptive power as compared with the others, pointing out the interesting fact that chemical union exercises a remarkable effect in this respect. It may be added that such compound gases, in intercepting so large a quantity of wave motion from a radiant source, necessarily become much heated. Air, being a mechanical mixture, on the other hand, is virtually transparent to radiant heat; hence the sun's heat in passing through it, or even the most calorific source we can employ, fails to raise its temperature to any sensible amount.

271. Influence of Aqueous Vapour.—The aqueous vapour constantly present in the atmosphere—though it affords a comparatively free passage to the solar heat—exercises an important influence upon terrestrial radiation. The sun's rays, by their contact with the surface of the earth, are changed in character; the luminous radiation is converted into obscure radiation. Now, as proved by experiment, aqueous vapour is particularly opaque to rays of obscure heat; it follows, therefore, that this substance, though existing in comparatively small quantity in the atmosphere, must materially prevent the passage of heat from the warmed earth.

Tyndall has shown that air, more or less charged with aqueous vapour, may exert from 30 to 70 times the absorptive effect of dry air, and expresses his belief that from 10 to 15 per cent. of the earth's heat is intercepted within ten feet of the surface. He remarks—"This is of the utmost consequence to the life of the world. Imagine the superficial molecules of the earth trembling with the motion of heat, and imparting it to the surrounding ether; this motion would be carried rapidly away, and lost for ever to our planet, if the waves of ether had nothing but the air to contend with in their outward course. But the aqueous vapour takes up the motion of the ethereal waves, and becomes thereby heated, thus wrapping the earth like a warm garment, and protecting its surface from the deadly chill which it would otherwise sustain."*

272. Equality or Reciprocity of Radiation and Absorption.—It is found that a body which is a good radiator is

* "*Rede*" *Lecture* (1865), by Tyndall.

also a good absorber of heat; on the other hand, a bad radiator is a bad absorber. Experiment goes further, and establishes the fact that these two qualities in the same body are strictly in proportion to each other. One method followed out was this: A large glass globe was taken, blackened on the inside, and having a thermometer fitted into it. The globe, being exhausted of air, was surrounded with ice at the freezing point, and the time was noted in which the thermometer was lowered a certain number of degrees. The globe was then quickly removed and immersed in a heated fluid of known temperature, and the time was again noted in which the thermometer regained its former temperature. It was found that these times were virtually the same, indicating that the radiation of heat from the bulb of the thermometer *towards* the sides of the globe took place at the same rate as the absorption of heat on the part of the bulb *from* the sides.

In reference to luminous rays, this principle is even more strikingly exemplified. From the researches of Kirchoff and B. Stewart, it would appear that for every definite ray—in other words, for a ray of any particular wave-length—the power of radiation in a body is precisely equal to its power of absorption; and, further, that this is true even for a ray polarised in any particular plane.

273. Illustrations of Radiation and Absorption.—There are several interesting experimental illustrations of the identity which subsists between the emissive and absorptive power of bodies. We select the three following:—

(1.) Take a porcelain plate with a well-marked pattern, say black and white. Place it in the fire and raise it to a white heat—now transfer it quickly into a darkened room. The pattern will appear to be reversed; those parts which were light, when the plate was cold, will now appear dark, and those which were formerly dark will now appear light. The explanation is this: The black and white pattern results from the *absorption* of the luminous rays on the part of the dark portions, and their reflexion or emission on the part of the light portions of the plate. But when the plate is raised to a white heat, the formerly dark parts radiate more perfectly than the light parts, hence the reversal in the appearance of the pattern.

(2.) Take a piece of well-polished platinum-foil and write a short word upon it in ink. Then hold it over the flame of a Bunsen burner in a dark room, and bring it to a bright red heat. The word will now appear brighter than the rest of the foil, indicating therefore a greater radiation from those parts covered by the ink. Again, if the other side of the foil be examined, the curious appearance is presented of *dark* letters upon a brighter ground. This is in consequence of the greater radiation from the letters, which necessarily leaves the parts behind *colder* than the rest of the foil.

(3.) Take a piece of rock-crystal, support it in a loop of platinum wire, and expose it to the flame of a blowpipe. In a dark room the platinum wire glows brightly, whilst the crystal scarcely glows at all. Here we have a body, though very transparent, and therefore a bad absorber, showing itself at the same time a bad radiator.

274. The Radiometer.—This remarkable instrument is a recent invention of Crookes. It is strikingly illustrative of the effects of radiation and absorption, though a considerable deal of mystery still hangs over the precise theory of its action. It consists of four thin mica discs (fig. 200), attached to the extremities of the arms of a vane capable of rotating freely on the top of a glass rod, running up from the bottom of an exhausted glass vessel of the form represented in the figure. The corresponding sides of the discs are well blackened, whilst the other sides are left untouched. On lighting a lucifer match and holding it near the bulb, the vane rotates, the blackened faces being *repelled.* The match being allowed to burn for a short time, and then blown out, the glowing part of the match held near the bulb produces the same effect. When exposed to the rays of the sun, or to the heat of a live ember taken out of the fire, the rotation is quickened—the vane spinning round with considerable velocity.

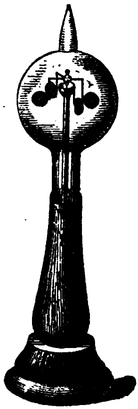


Fig. 200.—The Radiometer.

As to the theory of its action, considerable difference of

opinion exists amongst physicists. One explanation is this: The blackened surface absorbs more of the ethereal waves than the other; it is therefore subjected to greater impact from these waves than the other, and on this account the rotation takes place. This at first sight is plausible; but it has been found that, under certain circumstances, an *inverse* motion takes place. Recent experiments, for example, have shown that when the instrument is exposed for some time to the direct rays of the sun, and then plunged suddenly in a vessel of cold water, the *direct* motion soon ceases, and the vane rotates in the opposite direction; but, owing to the small quantity of heat accumulated, the inverse motion is quick at first, and then rapidly diminishes, ceasing altogether in the course of half-a-minute or so, when the direct motion again sets in, if the vessel is of glass and transparent. This result would seem to falsify the theory, for, according to Art. 272, the radiation from the blackened surface ought to proceed as freely as the absorption in the former case, and therefore the reaction ought to take place in the same direction. Another theory is, that the rotation is due to the reactionary effect of the dilatation of the residual air in the vessel; but this is unsatisfactory.

The effect has also been ascribed to electricity. It is asserted that the radiant source electrifies the bulb *negatively* on its exterior surface, inducing positive electricity on the interior, and that the blackened face, by direct radiation, becomes positively, and the bright face negatively, electrified. But inasmuch as the positive electricity of the inner surface of the bulb is nearer the discs than the negative electricity of the outer surface, there is produced, therefore, the *repulsion* of the blackened face. The *inverse* motion referred to above is difficult of explanation, however, on this theory.

The real cause of the action of the instrument, it may be inferred, is yet to seek.

275. Diathermancy.—This term was applied by Melloni to designate the *power of a body to transmit radiant heat.* The property has the same meaning, in regard to heat, as transparency has to light. It must be observed, however, that a body which is transparent to light, does not necessarily possess diathermancy. If we take a thin glass cell, with

parallel sides, for example, filled with water, and interpose this between some heating source and the thermo-pile, we find a very small deflection on the needle of the galvanometer, indicating that little heat has passed through the water-cell. The same medium, therefore, which allows light freely to pass, may arrest the transmission of heat.

Melloni was the first who made a thorough investigation into this matter. His experiments showed a remarkable difference between bodies in this respect, and his results have been confirmed, though with slight modifications, by subsequent experimenters. It is to him, therefore, we owe most of our knowledge on this subject. In his experiments on solids he made use of several sources of heat, among which were an incandescent platinum wire, a plate of blackened copper maintained at a temperature of 400° C., and a copper tube filled with boiling water. The total radiation from these sources he estimated by exposing the thermo-pile directly to each of them; he then interposed the substance under examination, and observed, in each case, the deflection of the galvanometer. He was thus enabled to compare the percentage of transmission with the total radiation. The following table contains some of his results:—

DIATHERMANCY OF SOLIDS.

Name of Substance. Thickness 2·6 millimetres ($\frac{1}{10}$th inch).	Percentage of Total Radiation.		
	Incandescent Platinum.	Copper at 400°C	Copper at 100°C
Rock-salt,	92·3	92·3	92·3
Fluor-spar,	69	42	33
Iceland-spar,	28	6	0
Glass,	24	6	0
Felspar,	19	6	0
Tourmaline (deep green),	16	3	0
Selenite,	5	0	0
Natural amber,	5	0	0
Alum,	2	0	0
Ice,	0·5	0	0

The numbers in the above table are very instructive. We know that different sources of heat emit different kinds

of calorific rays, that is, they give rise to waves of different lengths, and these are absorbed by bodies in very different proportions. This is borne out very forcibly by the different numbers. Rock-salt appears to be the only substance which allows comparatively free transmission to waves of all lengths. Glass, though transparent to luminous heat, is singularly opaque to obscure heat. As the sun's radiation consists in a large measure of luminous heat-rays, we can understand why the panes of glass in a window are not much heated even by brilliant sunshine. By their contact with different objects, however, they are changed into obscure rays, and as such cannot re-traverse the glass. Hence the reason why a room exposed to a summer's sun gets so heated—the glass, though allowing the sun's heat to pass in, serves as a barrier to its getting out. Hence also the high temperature of green-houses and photographic apartments after strong sun-shine.

The effect of a glass screen placed in front of a fire is well known. The calorific rays being in a large measure intercepted, the screen becomes warm, but radiates its heat in all directions, and thus the heat of the fire is mitigated, though at the same time we have its pleasant light.

The two substances rock-salt and alum are of use in separating the light and heat which radiate from the same source. The former, when covered with lamp-black, transmits the heat freely, but arrests the light; whilst the latter arrests the heat and transmits the light. Hence a combination of the two is practically impervious to both light and heat.

It has been more recently proved that, in general, a body is more opaque to its own rays when heated, than to a different body at the same temperature. Thus a plate of rock-salt absorbs more of the heat radiated from a hot plate of the same material, than from a plate of glass at the same temperature.

276. Influence of Thickness.—It can be readily imagined that the thickness of a body must affect its diathermancy. A plate of glass, for example, which is opaque at a certain thickness, may be so reduced as to show considerable diathermic power. The following table gives some of Melloni's results with plates of glass of different thickness:—

Thickness in Milimetres.	Percentage of Total Radiation.		
	Incandescent Platinum.	Copper at 400°C.	Copper at 100°C.
2·6, ...	24	6	0
0·5, ...	37	12	1
0·07, ...	57	34	12

These experiments indicate that we must consider absorption, and therefore radiation, not to be merely surface-phenomena, but as taking place throughout the mass of the substance.

277. Diathermancy of Liquids.—Melloni examined a number of liquids with the same object. He used an argand lamp as his source of heat, and he enclosed the liquids in a thin glass cell with parallel sides. His experiments with the liquids in the annexed table gave the following numbers:—

DIATHERMANCY OF LIQUIDS.

Name of Liquid (thickness of liquid layer=9·21 mill.)	Percentage of transmission.
Bisulphide of carbon,	63
Essence of turpentine,	31
Naphtha,	28
Sulphuric ether,	21
Sulphuric acid,	17
Nitric acid, Alcohol,	15
Strong solution of sugar,	12
Distilled water,	11

The numbers in the above table were obtained after making allowance for the effect of the glass cell.

Tyndall has since discovered that iodine, dissolved in bisulphide of carbon, whilst it quenches the strongest light, allows the heat very free passage.

278. Identity of Light and Radiant Heat.—We are now in a position to notice the general similarity which obtains between light and radiant heat. The analogies may be stated thus:—

(1.) *Each is a mode of motion.*—The vibrations of the ether give rise to both, with this difference, that the wave-lengths in light are *shorter* than those in heat.

(2.) *Both are propagated in straight lines* through any homogeneous medium. As a consequence of this, both obey the law of inverse squares. Moreover, the velocity of propagation is the same.

(3.) *Both are capable of reflexion and refraction.*—The focus for light is found to be also the focus for heat. Light in passing through a prism is broken up into distinctive colours, or rays of different wave-length; the radiant heat passing through the same prism is, in like manner, dispersed and divided into rays of different wave-length. This shows us that both light and heat consist of radiations of various kinds.

(4.) *Both exhibit the phenomenon of interference.*—Employing a narrow thermo-electric pile, and placing it in the light and dark bands on the screen, in fig. 137, we find the galvanometer much more deflected in the former than in the latter. This at once indicates that more heat falls upon the pile in the light bands than in the dark ones; and, therefore, that in the latter the heat-rays sent off from the reflectors interfere with each other.

(5.) *Both are capable of polarization.*—Forbes was the first who discovered the interesting fact that radiant heat may be polarised. Recent experiments have completely verified his result, and that both plane and circular polarization may be obtained.

CHAPTER IX.

DYNAMICAL PRINCIPLES—MUTUAL CONVERTIBILITY OF HEAT AND WORK—MECHANICAL EQUIVALENT OF HEAT.

To enable the student to have a clear understanding of the contents of this chapter, it is desirable that he should be made acquainted with certain principles in dynamics, which are taken advantage of.

279. How Work is Measured.—*Work* is said to be done by a force when that force overcomes resistance. In this country, the *unit* of work usually adopted is the power or force necessary to raise a weight of one pound through a height of one foot—it is usually known as a "foot-pound."

The work done by any living or inanimate agent is measured, accordingly, by the product of the weight moved in pounds, and the height in feet through which it is lifted. Thus if a man lift 5 lbs. 2 ft. from the ground, he is said to perform 5×2, or 10 units of work; expressed otherwise, the work he performs is 10 foot-pounds. Or, again, if a steam engine raise 10 cwt. of coal from a pit 20 fathoms deep in a certain time, the work performed by the engine in that time is expressed by $10 \times 112 \times 20 \times 6$ or 134,400 foot-pounds.

280. Relation between the Velocity of a Body Moving under the Force of Gravity and the Space Described.—It is proved in dynamics, that the relation between the *velocity* of a body falling under the force of gravity, and the *space* it describes, is given by the formula

$$v^2 = 2gs,$$

where v = velocity, s = space, and $g = 32$ (which number expresses the velocity, in feet, which the body acquires after falling for one second). Hence we can easily find the velocity of a body after it has fallen through a given height.

EXAMPLE I.—A body falls from the top of a tower 100 ft. high; find the velocity it has acquired on reaching the ground.

Here $v^2 = 2gs = 2 \times 32 \times 100 = 6400$, and $v = 80$ ft. *Ans.*

N.B.—The true meaning of this result (80 ft. per second) is that, supposing the body to be uninfluenced by the force of gravity *after* it has fallen 100 ft., and allowed to proceed on its course, it would move uniformly at this rate.

EXAMPLE II.—Find the velocity a body acquires in falling from the height of 772 ft.

$v^2 = 2gs = 2 \times 32 \times 772 = 49{,}408$, and $v = 223$ ft. (nearly). *Ans.*

It follows from this formula that the height is proportional to the square of the velocity. Now when a body falls upon an object *heat* is generated, and the amount of heat is in proportion to the height fallen through; hence the heat generated by a body falling upon or striking an object is *proportional to the square of the velocity.*

281. Conversion of Heat into Work.—That heat is convertible into work is evident when we reflect that it is through its agency we put in operation the various forms of engines that have been devised. Such machines have their parts so arranged as to convert, as far as possible, the effects of the steam generated by the heat into mechanical work, whether that be for the purposes of locomotion or for the varied processes connected with productive industry. The more effectively the conversion is carried out with a given expenditure of fuel, the more perfect is the contrivance.

A striking illustration of the conversion of heat into mechanical action is afforded by an apparatus known as the "Trevelyan Rocker," from the name of the inventor. It consists of a truncated wedge of brass (fig. 201), with a

Fig. 201.—"TREVELYAN" ROCKER.

narrow groove running along its under side, attached to a handle which terminates in a knob. The rocker, being put in the fire and raised to a red-heat, is then placed upon a

leaden support, as in the figure, with the knob of the handle resting upon a table. A brisk oscillatory motion ensues, giving rise to a clear musical note, which gradually diminishes in intensity as the rocker sinks in temperature. Its action is thus explained: By the heat causing a sudden expansion of the lead at the points of contact, the rocker is tilted to one side; falling on a cool part of the lead, the new points of contact suddenly expand, and it is tilted back again. The same thing being repeated, a series of taps follow each other in rapid succession, and occurring at regular intervals, a continuous sound is elicited.

282. Conversion of Work into Heat.—The converse proposition that work is convertible into heat, in other words, that heat can be generated by mechanical means is equally true. The *mechanical* sources of heat are (1) friction, (2) compression, and (3) percussion or impact.

(1.) *Friction.*—We have many familiar examples of the development of heat by friction. The ready ignition of a lucifer match in this way is due to the fact that the chemical material at the tip is thrown into combustion by a small quantity of heat. The ancient method of lighting a fire is said to have been to thrust the end of a round stick between two pieces of wood, and to make it rotate rapidly by means of a bow and a string of catgut. A common method among savages consists simply of rubbing briskly upon each other, two pieces of a particular kind of wood which have been prepared and well dried. In the case of striking flint and steel together, in the grinding of a knife, or in the quick stoppage of a railway train as it nears a station, the sparks of fire are really due to the minute metallic particles which have become detached, being raised by the excessive friction to a glowing state. The heating of a saw working through wood, the warmth produced in the hands when rubbed together, the heating of the axles of wheels when lubricants are neglected, are all examples of the same thing.

Fig. 202 represents an apparatus devised by Tyndall which illustrates the same truth. A brass tube is placed on a whirling stand; it is filled with water, and corked up. Two pieces of wood, with a groove cut in each of them, are jointed with a hinge, and are made to embrace the tube with

sufficient tightness. The tube being made to rotate rapidly, the friction develops such an amount of heat as to boil the water, and in a short time the cork is driven out with a loud report.

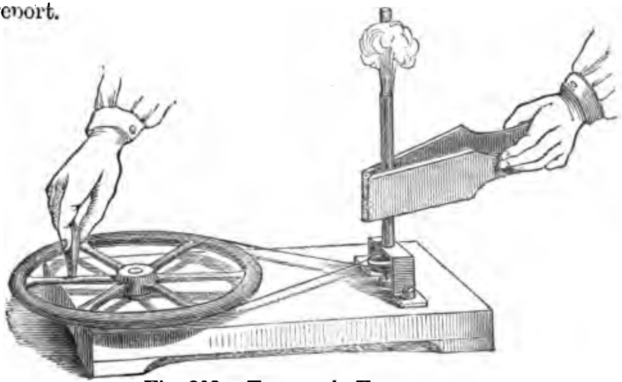


Fig. 202.—TYNDALL'S EXPERIMENT.

Davy was the first to perform the interesting experiment of fusing ice by rubbing two pieces together.

In all such cases the work performed in overcoming the friction expresses itself in the form of heat; and the greater the amount of the work—in other words the greater the muscular effort expended, the greater the development of heat.

(2.) *Compression.*—In the experiment referred to in Art. 226, we have an illustration that compression also generates heat. In condensing air into a vessel by a syringe, it is always found that both the syringe and the vessel are sensibly heated; if the operation be continued for some time, indeed, the syringe can scarcely be touched with impunity. If the syringe be removed, and the vessel be allowed to cool down by radiation, the confined air and vessel resume their original temperature, viz., that of the external air. Under those circumstances, let the stop-cock be opened, and let the air rush out upon the face of a thermo-pile, the needle of the galvanometer is deflected, and indicates that a *chill* has been produced. In such a case, the heat called forth by the compression, having disappeared, is no longer available; the con-

densed air has, therefore, as it were, to draw upon itself. It performs the work of expelling its own particles from the vessel, and as this involves an expenditure of heat, the escaping air is in consequence chilled.

(3.) *Percussion or impact.*—It is a well-known fact that a piece of iron beat with a hammer upon an anvil becomes warm. So much heat has been generated in this way as to make the iron nearly red-hot. When a bullet hits a target, sparks of fire are frequently seen. Such facts afford conclusive evidence of the development of heat from this cause.

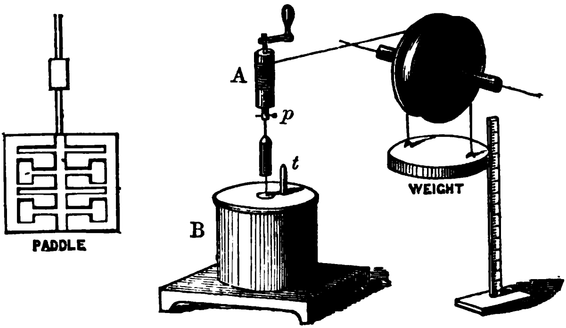


Fig. 203.—"Mechanical Equivalent" Determined.

283. Mechanical Equivalent of Heat.—It is to Joule we owe the determination of the exact numerical relation between heat and work. He devised the apparatus in fig. 203 for this purpose. B is a copper vessel filled with water, in which there revolves a system of paddles, one of which is represented at the side. The common axis of the paddles is connected by a movable pin *p*, with a vertical cylinder A. From this there passes a cord in connection with a pulley, moving on friction wheels, and from the axis of which there depends a weight. The descent of this weight is indicated on a graduated scale in feet and inches. The weight being wound up, which can be done by detaching the pin *p*, and thus not moving the paddles, the pin is replaced, and the weight allowed to descend; this causes the paddles to revolve; they agitate the water and raise its temperature. This operation

being repeated several times, the temperature of the water is then noted, as given by the thermometer *t* placed in the vessel. To prevent the rotation of the water, the paddles pass through fixed partitions in the vessel, resembling in form the paddles themselves.

In this way, and by a number of very careful experiments, Joule established the fact that *to raise* 1 *lb. of water* 1°*F. requires the expenditure of as much work as would raise* 772 *lbs. one foot*, or which is the same thing, 1 *lb.* 772 *feet.* This number, "772 **foot-pounds*," is therefore known as the *mechanical equivalent of heat.* If we adopt the centigrade scale, the number is 1390 foot-pounds, which, of course, implies that the amount of heat required to raise 1 lb. of water 1° C., is such as, when applied mechanically, would lift 1390 lbs. one foot.

Joule further showed that *the absolute amount of heat generated by a given expenditure of work is fixed and invariable.* He was led to lay down this principle by experimenting in various ways. For example, in causing discs of cast-iron to rub upon each other, he measured the amount of heat developed, and the force expended in overcoming the friction. Again, in urging water through capillary tubes, he did the same thing. He found, in such cases, that the above principle, making due allowance for difference in the specific heats of the substances, was accurately correct.

284. Problems on Joule's "Equivalent."—There are certain problems connected with the mechanical equivalent of heat, which the student would do well to notice. The following examples will sufficiently illustrate the methods of solution.

EXAMPLE I.—A leaden ball falls from a height of 3860 ft.; supposing all the heat generated to be communicated to the ball, what would be its rise of temperature?

The ball in falling 772 ft. would raise an equal weight of water 1° F., therefore in falling 3860 ft., which is 5×772, would raise the water 5° F. But the specific heat of water is thirty times that of lead, hence on the given supposition the ball would be raised in temperature $5 \times 30 = 150°$ F. *Ans.*

* Some recent experiments under the auspices of the British Association have been undertaken by Dr. Joule, with the view to test this result. The *mean* of 60 experiments gave 772·2 *foot-pounds.*

Example II.—A 68-pound cannon ball strikes a target at a velocity of 1400 ft. a second. Supposing all the heat generated by the collision to be communicated to 68 lbs. of water at 60° F.; how many degrees would the temperature of the water be raised? (May Examination, 1869.)

The ball, on striking the target with a velocity of 223 ft. per second (Art. 280), would generate heat sufficient to raise an equal weight of water 1° F. But by the question it strikes it with the velocity of 1400 ft., that is, with a velocity nearly $6\frac{2}{7}$ times this amount, and the heat generated is proportional to the square of the velocity, hence the ball would raise the water $(6\frac{2}{7})^2$ degrees F., or $39\frac{25}{49}$° F. *Ans.*

N.B.—If the heat were communicated to the ball (suppose it constructed of iron), then since the specific heat of water is about ten times that of iron, the temperature of the ball would be ten times this amount.

Example III.—A weight of a ton is lifted by a steam engine to a height of 386 ft.; what is the amount of heat consumed in this act? (May Examination, 1873.)

By lifting 1 lb. 772 ft., a quantity of heat is generated sufficient to raise 1 lb. of water 1° F. Now by the question the engine executes work equivalent to 2240×386 foot-pounds, hence it consumes a quantity of heat $= \dfrac{2240 \times 386}{772} = 1120$, that is, a quantity such as would raise 1120 lbs. of water 1° F. *Ans.*

Example IV.—Two balls, each weighing 3 lbs., are moving in opposite directions with a common velocity of 446 ft. Supposing them to collide, and that the heat generated by the impact is imparted to 5 lbs. of water; how much would the temperature of the water be raised?

The quantity of heat generated in each ball by the impact would raise 3 lbs. of water 4° F. (Ex. 2); therefore the heat generated in the two balls would raise 6 lbs. of water 4° F. But the heat must be inversely proportional to the quantity of water; hence $5 : 6 :: 4 = 4\frac{4}{5}$, that is, the 5 lbs. of water would be raised $4\frac{4}{5}$° F. *Ans.*

285. Disposal of Heat in a Steam Engine.—The steam generated in the boiler of a steam engine receives a *definite* amount of heat from the furnace. This heat is in part consumed by the conduction of, and consequent radiation from the containing vessels, and in part lead away into the condenser, or into the external air, whilst the remainder is expended upon mechanical work, viz., driving the piston to and fro in the cylinder. If we had the means of collecting the heat that was dissipated by the two first causes, we should find, reasoning from modern views, that the sum of

the amounts thus lost differed from the *original* amount, by just what is expended in mechanical energy. We naturally infer, therefore, that were it possible to reduce the loss from these causes, we should produce a greater amount of mechanical effect, under a given amount of heat originally imparted to the steam.

286. Dynamical Theory.—The *material* theory in regard to heat, viz., that it is a kind of matter, or impalpable substance stored up in a body, has been quietly ignored in these pages, and for this reason, that the explanation of the different phenomena on this theory is quite unsatisfactory.

The dynamical theory, on the other hand, that heat is due to molecular motion or vibration, is at once adapted to elucidate these phenomena. Perhaps the real *experimenta crucis* of this theory, as in the case also of the undulatory theory of light, are nowhere better found than in the phenomena of "interference" and "polarization." The truth is, that modern research has so strengthened this theory as to put it altogether beyond the pale of doubt.

287. Explanation of Latent Heat. — During the conversion of a solid into a liquid, or of a liquid into a gas (Art. 239), the thermometer remains stationary. The materialists proposed the term "latent" to be applied to the heat which was thus rendered insensible. The term is preserved amongst modern physicists, but a new insight is thrown upon the phenomenon by the adoption of the dynamical theory. What takes place is this: In either case the heat passing in is expended on the breaking up of the molecules—it really performs work—it is not lost, but is occupied in the tearing up of the atoms, by which they assume new positions, and acquire *potential* energy, or power to execute work. In the former case, the heat is expended in *interior* work only; in the latter it has not only interior work, but a certain amount also of *exterior* work, in opposing the atmospheric pressure, so as to rise in the form of vapour. We can understand, therefore, the difference in the estimates of the latent heat of fusion, and that of vaporization.

APPENDIX.

DOCTRINE OF ENERGY.

1. **Energy** is the *power to do work;* it exhibits itself in many different ways, and always undergoes change when work is done.

Every mass of matter in motion possesses energy, and is in consequence able to do work. Thus a ball thrown upwards has, at the moment it leaves the hand, a store of power which enables it to rise in opposition to gravity through a certain distance; in other words, it is enabled, in virtue of the velocity imparted to it by the hand, to lift its own weight to a certain definite height. But the ball in its ascent has continually to resist the pull of gravity, and, consequently, as it rises, its velocity becomes less and less, until at length it comes momentarily to rest. Let us now suppose the ball to be supported at this height by lodging on the eaves of a building, near the edge, so that a small displacement will liberate it. In this position it will lie and exhibit no more evidence of energy than a similar ball lying on the ground. The ascent of the ball represents so much work done, and the energy which performed it is no longer visible, since the ball is now at rest.

2. **Energy is not Destroyed in Performing Work.**—The performance of work does not involve the destruction of energy, but simply a change in its form; energy being as indestructible and unalterable in amount as matter itself. To apply this to the ball supposed to be lying on the eaves of a building, we will compare its position with that of a similar ball lying on the ground. In each case there is a

mutual attraction between the ball and the earth, but this attraction, in the present position of the balls, is powerless to produce motion. Let, however, each ball be slightly displaced and the case is very different. The ball on the ground is as badly situated as before, with regard to being affected by the earth's attraction, but the ball liberated from the building is able to move towards the earth in virtue of this attraction, and in so doing the energy which disappeared while the ball was rising now reappears in it.

It is evident, therefore, that while the ball rests upon the building its position is one of advantage, for the arrangement is such that the original form of energy, viz., matter in motion, can be recovered by simply displacing the ball from its support; and the laws of falling bodies declare to us that the ball will reach the ground with precisely the same velocity as that necessary to be imparted to it, in the opposite direction, to enable it to rise to the height from which it has fallen. It follows, therefore, that the ball in falling to the ground ultimately acquires the same amount of actual energy as that which it originally possessed when first projected upwards.

3. Actual and Potential Energy.—It has just been shown that a ball in motion, and a ball resting upon the eaves of a building both possess energy, the former on account of its motion, the latter in virtue of its position. It has also been shown that these two conditions of energy, although widely different in character, are easily convertible, the one into the other.

The energy of a body in motion is called *actual* or *kinetic energy*, while that of an arrangement which is capable of yielding actual energy when nothing prevents its doing so, is called *potential energy*. As instances of arrangements possessing *potential* energy may be mentioned: a lifted hammer; the wound-up weight of a clock; a reservoir of water on a hill; a compressed spring; a drawn bow; a loaded air-gun.

4. Measurement of Energy.—Energy is measured by the amount of work it is able to perform. The kinetic energy of a body in motion, or *accumulated work*, as it is sometimes called, is proportional to the mass of the body, and to the

square of its velocity; it is expressed by the following formula:—*

$$\frac{MV^2}{2g},$$

where M is mass in lbs., V velocity in feet per second, and g gravity ($=32 \cdot 2$). An example will be useful to illustrate the use of this formula: *A cannon ball weighing* 60 *lbs. is moving at the velocity of* 2000 *ft. per second; what amount of energy does it possess?* By the above formula—

$$\frac{MV^2}{2g}=\frac{60 \times (2000)^2}{64 \cdot 4}=3,726,708.$$

That is, the cannon ball possesses sufficient energy to perform 3,726,708 units of work.

5. **Kinetic Energy and Momentum.**—Kinetic energy must not be confounded with *momentum*. The latter is defined as the product of the mass of a body into its velocity simply; it is an expression for the *quantity of motion* possessed by a moving body. To obtain a clear idea of quantity of motion, suppose a moving body to be made up of a definite number of small particles of equal mass, and let one of these particles, moving with a given velocity, be regarded as a unit quantity of motion; then, of course, the velocity being constant two particles will have between them double the motion of one, three particles treble the motion, and so on, the sum of the unit motions being proportional to the number of unit particles, which implies that the momentum is proportional to the mass. In the next place, suppose a body of definite mass to have its velocity doubled, it will then travel two feet in the same time that it before travelled one, that is to say, the amount of motion in a given time is doubled; with a treble velocity it would be trebled, and so on, the momentum increasing with the velocity.

Kinetic energy takes no consideration of the momentum of a body, as such, but simply expresses what a body in motion can do in opposition to forces.

A good example, illustrating the difference between kinetic energy and momentum, is the distribution of motion which

* The *proof* of this formula will be found in elementary works on Mechanics.

takes place when a ball is fired from a cannon. It is well known that when a shot is fired from a gun, the latter recoils. This is in accordance with Newton's third law of motion, *that action and reaction are equal and opposite.* It is to be understood then that the exploding gunpowder communicates equal momenta to the ball and to the gun; but the mass of the gun being very great compared with that of the ball, the momentum it receives gives rise to a small velocity only; while to the ball of much smaller mass it gives a very great velocity.

A moment's reflection will show that, although the ball flies from the gun, and the latter recoils with precisely equal momenta, they possess very different amounts of energy. The recoil of the gun is soon suppressed by friction; or, in the case of a sportsman's gun, by pressing it firmly against the shoulder. In either case the effect is insignificant compared with that of the blow delivered by the projectile. It is owing to the superior velocity of the ball that it possesses such a large share of the total energy distributed by the exploding gunpowder.

6. **Various Forms of Energy.**—We have hitherto considered energy as matter in visible motion, or potential arrangements equally visible. But there are several other forms, some potential, some kinetic, which energy assumes. A short space will be devoted to each of these.

7. **Heat.**—Heat is a variety of energy, for if we bring two bodies, one hotter than the other, into contact, heat passes from the hotter to the colder body, and this transference of heat is capable of giving rise to work, as it does in the case of the steam engine, where the heat of the burning coals is transferred to the water in the boiler, part of which it converts into steam. The latter, being generated under pressure, possesses great elastic force which enables it to overcome the inertia of the piston and the machinery to which it is connected.

8. **The Energy of Heat is Kinetic.**—The energy of a hot body is evidently kinetic, not potential. Thus a cold body in contact with a hot one immediately grows warmer, in consequence of heat transferred from the hot body, just as a body at rest, or moving with small velocity, receives additional velocity on coming in the way of a moving body

having a greater velocity than its own. Also, we know, by observation, that a hot body in the presence of cold bodies becomes cooler, and the cold bodies become warmer, even when there is not contact between the hot and cold bodies. It is further shown by experiment that if the hot body, or the cool body, or both, be placed in a vacuum, the cooling of the warm body and the warming of the cool one still goes on. The warm body is said to radiate heat, which the cool body absorbs, and it is clear that energy in some form or other passes from the hot to the cold body.

9. **Latent Heat.**—During the melting of a solid, and the evaporation of a liquid, a definite amount of heat disappears; but, inasmuch as the molecules of the body thereby become pushed apart to a greater extent than they were before in in opposition to cohesion, which tends to hold them together, we perceive that work is performed—molecular or interior work. The molecules of a vapour, or liquid, are, however, in a position of advantage, for when the temperature of the substance is sufficiently lowered, the molecules are at liberty again to move towards each other, and thus reproduce sensible heat. The condition of energy called *latent heat* is, therefore, potential.

10. **Radiant Energy.**—Under this head are included the various undulatory motions of the ether produced by the molecular movements of heated bodies. These undulations are absorbed more or less by all bodies upon which they impinge, and the bodies become heated in consequence. For this reason ethereal undulations are called *radiant heat*, a term which is in very general use, but which must be always understood to mean undulations of the ether, or heat producing rays, and must not be confounded with the molecular motion called *heat*, which is a very different thing.

What we call *light* is simply certain rays of radiant heat, which are capable of influencing the retina of the eye in such a way as to produce vision.

11. **Electricity.**—It is a principle in electricity that *two bodies charged with opposite kinds of electricity attract each other*. Such bodies would approach each other if allowed. So long as they are prevented from doing so, their separation implies potential energy.

12. **Chemical Affinity** is a peculiar attractive force exerted between the ultimate atoms of matter. This force varies very much in intensity in different cases: thus while the gases hydrogen and oxygen have a powerful affinity for each other, oxygen and gold have but little affinity. Two separate substances having an affinity for each other are capable of undergoing a particular kind of union called chemical combination, and in so doing they generate heat; they therefore, before combination, represent a store of potential energy. Gunpowder, which is a mixture of nitre, charcoal, and sulphur, contains a great store of energy in the mutual affinities of its constituents. A part of this store is capable of being directly converted into kinetic energy by using it to project a heavy shot from a gun. Coal, wood, and other combustible bodies, considered with respect to the free oxygen of the air, are stores of potential energy; for they may be burnt, and thus give rise to heat.

13. **Summary of the Varieties of Energy.**—The following is a summary of the principal forms under which energy presents itself, with examples:—

POTENTIAL ENERGY.

I. **Gravitation of separated Masses of Matter** (visible energy of position).—EXAMPLES—A lifted hammer; the relation of the earth and moon to each other.

II. **Cohesive Attraction of Separated Molecules** (molecular separation).

a. The result of exterior work.—Tension in a solid, the molecules of which are separated beyond their normal position of equilibrium, but within the limits of elasticity. EXAMPLE—An india-rubber tube stretched between two fixed points.

b. The result of interior work.—The considerably separated molecules of a liquid, and the freely separated molecules of a gas or vapour, which are capable again of cohering to a liquid or solid, and in so doing reproduce the kinetic energy which disappears when solids become liquids, and liquids vapours (latent heat). Also the separation of the molecules of solids, liquids, and gases, due to expansion by heat.

III. **Electrical Attraction of Oppositely Charged Bodies** (electrical separation).—EXAMPLE—The inner and outer coatings of a charged Leyden jar.

IV. **Chemical Affinity between Separated Atoms** (atomic separation).—The mutual attraction exerted between atoms of matter possessing different intrinsic properties. EXAMPLES—Gunpowder; coal with respect to the oxygen of the air.

KINETIC ENERGY.

I. **Motion of Masses, Mechanical Motion, or Visible Energy.**—EXAMPLES—A falling stone; the earth moving in its orbit.

II. **Motion of Moelcules, or Heat** (absorbed heat).

III. **The Flow of Electricity from Higher to Lower Potential.**—EXAMPLES—The discharge of a Leyden jar; the energy of a Voltaic circuit.

Two cases not given in the above summary may be remarked on here; these are radiant energy, and the potential energy of a compressed elastic body.

In radiant energy the particles of ether taking part in the transmission of the undulations, move alternately to and fro, like a pendulum, or vibrating string. Oscillating or vibrating bodies assume the potential and kinetic forms.

When an elastic body is compressed it exhibits *as a whole* potential energy; but the energy of the body really resides in the kinetic energy of its molecules. The effect of compression, leaving out of account changes of temperature, is to increase the number of moving molecules in a given space, and hence to increase their pressure, or the effect of their combined impact, per unit area.

14. Transmutation of Energy.—Taking any particular form of energy, we can, by means of proper arrangements, convert it into any other form of energy, often directly, but sometimes it is necessary to cause the energy to pass through one or two intermediate forms. We tabulate here the possible transmutations, with examples of each:—

I. **Visible Potential Energy** into—

2. *Visible kinetic energy.*—EXAMPLE—A falling weight, such as the ram of a pile engine, or the descending weight of a clock.

II. **Visible Kinetic Energy** into—

1. *Visible potential energy.*—EXAMPLE—A weight raised.
3. *Molecular separation.*—EXAMPLE—An elastic body stretched.
4. *Heat.*—EXAMPLES—A piece of cold iron hammered; two pieces of wood rubbed together,

6. *Electrical separation.*—Example—A dry glass rod rubbed with dry silk.

7. *Electricity in motion.*—Example—A magneto-electric machine turned.

III. **Molecular Separation** into—

2. *Visible kinetic energy.*—Example—An arrow discharged from a bow.

4. *Heat.*—Examples—Condensation of vapours; solidification of liquids.

IV. **Heat** into—

2. *Visible kinetic energy.*—Example—Heat applied to the boiler of a steam engine.

3. *Molecular separation.*—Examples—Fusion of solids; evaporation of liquids (latent heat).

5. *Atomic separation*—Example—Disassociation of the elements of water and other compounds at a high temperature.

6. *Electrical separation.*—Example—A crystal of tourmaline when heated exhibits opposite electricities at opposite ends.

7. *Electricity in motion.*—Example—One face of a thermo-electric pile warmed.

V. **Atomic Separation** into—

4. *Heat.*—Example—Combustion, and chemical combination in general.

6. *Electrical separation.*—Examples—Two different metals in contact; a Voltaic cell with its circuit broken, and the ends carried to a condenser.

7. *Electricity in motion.*—Example—A Voltaic cell with its circuit closed.

VI. **Electrical Separation into**—

2. *Visible kinetic energy.*—Example—An electrically excited glass rod brought near to a suspended pith ball.

7. *Electricity in motion.*—Example—The discharge of a Leyden jar.

VII. **Electricity in Motion** into—

2. *Visible kinetic energy.*—Example—Voltaic current supplied to an electric bell, or to an electro-dynamic machine.

4. *Heat.*—Example—Voltaic current made to traverse a very thin or badly conducting wire.

5. *Atomic separation.*—Example—Decomposition of water and other compounds.

6. *Electrical separation.*—Example—Charging of a Leyden jar by means of an induction coil.

15. Conservation of Energy.—It has already been stated that energy can never be destroyed. Whenever it disappears under one form it reappears under a new form; it is capable of an endless round of transformations, but suffers no loss. Whenever a transmutation of energy takes place, its value in foot-pounds, or other units, in the new form is exactly the same as in the original form. This is the principle of the conservation of energy, which may be stated generally thus: If there be in a system of bodies definite quantities, a, b, c, d, etc., of energy, of the forms, A, B, C, D, etc., respectively, and the sum $a + b + c + d +$ etc., be n, then at all times, and after any number of transmutations, providing no energy leaves or enters the system, the sum of the quantities, $p + q + r + s +$ etc., which may then appear, will also be n.

To simplify this statement; suppose we have 40, 30, 20, and 10 units respectively, of four kinds of energy, A, B, C, D, the sum of these is 100 units. Let now various transmutations take place, and the new quantities of A, B, C, D, be determined, the sum of these, in the same units as before, will be exactly 100 as at first; the new quantities may, for instance, be 25, 40, 0, 35, respectively.

The principle of the "conservation of energy" may be expressed shortly thus: *the various forms of energy in the universe, whatever be their transmutations, are always constant in amount.* It is undoubtedly one of the grandest generalizations of modern science.

EXAMINATION PAPERS OF THE SCIENCE AND ART DEPARTMENT.

From May 1872, to May 1876.

(ADVANCED STAGE).

1872.

1. The velocity of sound in water is about four times greater than in air, what is the cause of this difference?

2. What is the part played by the wooden portion of a violin in the production of its sound?

3. Describe an open organ pipe, and explain the production of a musical note by such a pipe.

4. Show by a diagram the condition of the air in closed and open pipes when their higher notes are sounded.

5. What is meant by the aberration of light?

6. What is meant by the adjustment of the eye for distinct vision, and how is the adjustment accomplished?

7. Dark clouds are composed of small transparent water particles, how can such particles intercept the light of the sun?

8. The rays of the sun are received upon a large converging lens, the focus being visible by the dust floating in the air. A screen placed in front of the focus shows a white circle surrounded by a red fringe, beyond the focus it shows a white circle surrounded by a blue fringe. Explain these appearances.

9. You stand before a looking-glass held in the hand of a friend, and observe your own image. Your friend moves away from you, carrying with him the mirror. Your image retreats at the same time. Prove that the motion of the image is twice that of the mirror.

10. The rails from London to Manchester are 188 miles long. Suppose these rails to form one continuous piece at a temperature of 0° C., what will their length be at 20° C., the coefficient of expansion of iron being ·0000118?

11. Describe some one means of determining the mechanical equivalent of heat.

12. A pound of lead at 50° C. is immersed in a pound of water of 0° C., what will be the resulting temperature of both, the specific heat of lead being ·031?

13. What is the effect of a transparent glass screen on the heat of a common fire?

14. Ice is formed on clear nights in India when the temperature of the air is 15° or 16° F. above the freezing point. How is this possible?

1873.

1. The velocity of sound in air at a temperature of 0° C. is 1,090 feet a second; the length of each sound-wave of a series in such air is four feet; how will you determine the number of vibrations executed by the body which produces the sound? Give the full reasons for your answer.

2. What is the length of an open organ pipe which produces sound-waves four feet long? What is the length of a stopped pipe which produces waves of this length? Give a clear reason for your answer, explaining what you understand by a sound-wave.

3. Two musical sounds, the one produced by 400 and the other by 410 vibrations a second, pass through the same air; describe and explain what is heard.

4. How are nodes produced on a vibrating string?

5. Describe and show by a diagram the character of the image produced by a convex mirror.

6. Describe and explain the character of the images formed by a concave mirror. Why do I employ the term *image* in the last question and the term *images* in this one?

7. The sun is 20 degrees above the horizon; placing my eye behind a plumb line I see the sun's image reflected from smooth water; what is the angle enclosed by the plumb line and the line drawn from the eye to the sun's image? Show by a diagram how the angle is determined.

8. I place a red ribbon successively in the green and the red of the spectrum; how is its temperature affected? I do the same with a green ribbon, how is its temperature affected?

9. There are parts of the Atlantic Ocean which seem almost black when looked down upon, while the water, if placed in a glass, seems particularly clear; explain the blackness.

10. You are provided with bars of copper, silver, gold, and platinum, and are required to devise a means of determining their conductivities for heat; how will you proceed?

11. You are provided with plates of the four metals mentioned in the last question, and are required to devise a means of determining their radiative powers; how will you proceed?

12. A weight of a ton is lifted by a steam engine to a height of 386 feet, what is the amount of heat consumed in this act?

13. Why, as a general rule, are white clothes cooler in summer than dark ones? If it could be proved, as it may be, that some dark bstances are cooler in the sunshine than some white ones, how ld you explain the fact?

1874.

1. A syren with twelve apertures rotates 2400 times in a minute: what is the length of the sonorous waves it produces in air of the freezing temperature?

2. Along four directions round a vibrating tuning fork no sound is heard. Draw a horizontal section of the two prongs of the fork, mark the four directions referred to, and explain the extinction of the sound in those directions.

3. A number of tuning forks stood silent upon a table, and at a distance from them a fork was sounded. On stopping the vibrations of the latter, one fork, and one only, of those upon the table was found sounding: explain the observation.

4. Two open organ-pipes are in perfect unison, being of the same length. I shorten one of them slightly: what will be the effect upon the ear when both of them are now sounded together? Explain the effect.

5. Explain, by aid of a diagram, the refraction of a beam of monochromatic light in a glass prism by the undulatory theory.

6. You hold a candle before a glass window, so that its rays fall nearly perpendicularly upon the glass, and place your eye so as to receive the reflected rays. Two images of the candle are visible: why only two?

7. A disk is so painted as to have six black and six white sectors. Shone upon by a steady light it is set in rapid rotation; the sectors disappear, and the disk becomes uniformly grey. Why? The steady light is now extinguished, and the disk is illuminated by a single electric flash: describe and explain the appearance observed.

8. I am long-sighted, and use spectacles, each glass of which is formed of two segments, one intended to give sharpness to distant objects, the other for ordinary reading: describe the characters of both glasses, and explain how they help the eye.

9. The solar beam, converged by a strong double convex lens, is brought to a focus in the air. A white screen is placed first between the lens and the focus, and secondly beyond the focus. The circle of light upon the screen is in each case surrounded by a coloured rim: state the colours, and explain their origin.

10. A thermometer placed in an open black box, and exposed to the sun rises to 80° F. A glass cover is placed on the box, and the temperature rises to 120°: explain this, and apply, if you can, your explanation to the possible influence of a planet's atmosphere in augmenting its temperature.

11. You are furnished with an ounce of each of the following metals, and are required to determine their specific heats: how will you proceed? Gold, silver, copper, iron, lead, bismuth. State, as far as you remember them, the results that you would obtain.

12. Explain fully the influence of pressure on the boiling point of

water, and state what you know regarding the influence of pressure upon the melting point of ice.

13. The gas which escapes from soda water may, by powerful pressure, be reduced to the liquid condition. When the pressure is removed the liquid returns to the state of gas, but in doing so it produces solid carbonic acid, which has the appearance of snow: explain this effect.

14. How do you suppose the heat of the animal body to be maintained?

1875.

1. A sound is propagated through air of the density of one atmosphere, and also through air of the density of two atmospheres. The temperature is the same in both cases: will there be any difference in the velocity of the sound? State the grounds of your answer.

2. Describe the manner in which the human voice is produced. Note the points of resemblance between the mechanism of the voice and that of the syren.

3. Describe the Eolian harp; state how it must be placed to elicit its sounds; and state the cause of the sounds.

4. From a vibrating disc, or bell, issues a mass of sound. By quenching certain portions, the remaining sound may be augmented in intensity. In other words, a part of the sound may be proved to be louder than the whole. Describe and explain an experiment which shall illustrate this.

5. Describe an experiment which shall prove the angular velocity of a reflected ray to be twice that of the mirror which reflects it. Prove, if you can, this proposition geometrically.

6. What is the meaning of spherical aberration as applied to a lens, and what is the meaning of chromatic aberration?

7. A double concave air-lens, plunged into water, produces an image like that produced by a double convex water-lens, in air. Explain the result by a diagram.

8. What are Fraunhofer's lines? Describe an experiment which shall illustrate their production artificially.

9. What is meant by plane-polarized light? State the circumstances under which a beam of light, reflected from glass, is *perfectly* polarized.

10. At what temperature does water reach its maximum density? State all that occurs while the water is warmed twenty degrees above this temperature, and while it is chilled twenty degrees below it.

11. What is the difference between the specific heat of a gas at constant volume and its specific heat at constant pressure? What is the cause of the difference?

12. What is meant by the coefficient of expansion of a gas? The coefficients of expansion of all gases are not far from being alike:

what do you suppose to be the reason? State the divergences from the general rule known to you.

13. How is "latent heat" explained by the dynamical theory of heat?

14. Explain what is meant by the mechanical equivalent of heat; and describe some of the methods by which it has been determined.

1876.

1. Show by three separate diagrams the nodes and vibrating segments of a bell when it sounds its fundamental note; and also the two notes of the bell next above the fundamental.

2. Show by three separate diagrams the nodes and vibrating segments of an open organ pipe when it sounds its fundamental note and its two first harmonics. Compare these nodes and segments with the corresponding ones of a stopped pipe.

3. A tuning fork vibrates 545 times in a second; what is the length of a column of air which, at the freezing temperature, will most perfectly resound to the note of the fork?

4. In some recent experiments made in the Straits of Dover, the sound of a cannon was heard only two miles off on a certain day, and more than ten miles off on the evening of that day. Can you give any explanation of the result?

5. What is meant by the "angle of minimum deviation" as applied to the refraction of a beam of light by a glass prism?

6. What is meant by the "limiting angle" in the case of the total reflection of a beam of light? Let your answer be illustrated by a diagram.

7. Describe Bunsen's photometer, and the mode of using it.

8. Describe an experiment by which the non-luminous ultra-red solar or electric rays may be brought to a focus, and caused to form an invisible image. How may the image be rendered visible?

9. State the principle of interference as applied to light, and bring the principle to bear in the explanation of the colours of the soap-bubble.

10. Describe a few experiments which shall clearly illustrate and explain the principle and application of the safety-lamp.

11. Can ice, at 32° F., and at the ordinary atmospheric pressure, have its temperature raised still higher? If not, why not? A beam of solar heat, sent through ice at 32°, is in part absorbed by the ice, will not the absorbed heat warm the ice? If not, what effect does the heat produce?

12. A definite column of steam, on entering the cylinder of a steam-engine, possesses a definite amount of heat, which is in part communicated to the cylinder, and in part carried away by the steam after it has done its work in the cylinder. Supposing all the heat thus communicated and carried away to be collected, would it, or would it not, be equal to the heat possessed by the steam imme-

diately before entering the cylinder? If there be a difference, what is its cause?

13. The sun radiates his heat towards the earth, and the earth radiates her heat towards stellar space. Do you suppose that the solar and the terrestrial heat pass with the same ease through the earth's atmosphere? Frame your answer so that I may learn what you really know of this subject.

14. A painted board exposed to the sky on a clear night covers itself with dew, a piece of polished silver exposed beside the board remains undewed. What is the reason of this difference?

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N.B.—*The figures refer to the Articles.*

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